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# Development of an integrated watershed-scale surface hydrologic modeling environment using ARC/INFO GIS

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# Development of an integrated watershed-scale surface hydrologic modeling environment using ARC/INFO GIS

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This is to certify that the master thesis of

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Signatures have been redacted for privacy

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## ABSTRACT

While lumped hydrologic models are adequate to address some of these surface water resource management issues, the cumulative management of watersheds and ecosystems requires development of new modeling approaches that explicitly incorporates various spatial variability of watershed and landscape properties. To enhance development and applicability of various new modeling approaches, geographic information systems (GISs) are now being widely used to acquire, store, manipulate, display, and visualize spatially distributed watershed data.

This study describes a watershed surface hydrologic modeling system (WSHMS) that was developed using the ARC/INFO GIS. WSHMS provides a user-friendly interface for modeling the hydrologic processes of catchments and basins. The hydrologic modeling consists of the following primary components: (1) an overland flow module that is based on the solution to the two-dimensional Saint-Venant's equation; (2) a channel flow computational module that is based on Manning equation; (3) an infiltration module that uses the Green-Ampt equation; and (4) a pre- and post-processing module for organization and display of input and output data. The pre- and post-processing module adopts the general form of a traditional graphical user interface to facilitate user navigation of the modeling system. An example application of WSHMS to the Walnut Creek watershed demonstrates its capability and usability.

# 1. INTRODUCTION

## 1.1 Overview

Surface runoff, deep percolation and the consequent off-site impacts of sedimentation and pesticide and nutrient transport to surface and groundwater system are influenced by the spatial and temporal variability of soils, topography, land cover and land use, climate, and other human-induced changes to the environment. However, most of the impacts of human activities on water resources originate from routine management of the land. Therefore, there has been an increasing need to predict surface hydrologic processes and to assess quantitatively how these processes influence water quantity and quality. Improved understanding of land surface processes has also become an important component of water resource management, particularly flood forecasting. Recently, a new trend that requires the determination of the interactions of watershed geomorphology with spatial heterogeneity of watersheds has emerged in the field of surface hydrologic modeling. To this end, a number of researchers have attempted to explain the heterogeneity in landscape characteristics and climate.

Accurate modeling of surface hydrology at various spatial (e.g., watershed, field) and temporal scales depends on how well the conceptual model incorporates processes and mechanisms that occur within the physical system as well as the volume and nature of the measured data for model confirmation and testing. Processes that influence surface hydrology include: infiltration, spatial and temporal variability in precipitation, evapotranspiration, the nature of the channel flow and channel morphology, and base flow.

Most of the existing surface hydrologic models vary in their representation of these processes and techniques used in obtaining solutions to the governing equations. Also, some of the existing model are deterministic, while others are stochastic by incorporating some elements of randomness. Recently, a number of voices have been heard calling for a new departure in surface hydrologic modeling that is based upon a clear understanding of the complex water balance relationship ( Burges, 1986; Beven, 1987; Dodge, 1988; Klemes, 1988). A more physically based, process-oriented, and user-friendly surface hydrologic model is required to address the ongoing problems of water quality and flooding.

The demands placed on hydrologic models have increased considerably in recent times. Although it was once sufficient to model catchment outflow, it is now necessary to estimate distributed surface and subsurface flow characteristics, such as flow depth and flow velocity. These flow characteristics are the driving mechanisms for sediment and nutrient transport in landscape and unless they can be predicted reasonably well, water quality models can not be expected to adequately simulate sediment and nutrient transport. Many hydrologic current models are difficult to use and do not completely utilize the functional components of GIS.

**1.2 Specific Objectives**

This research was initiated to develop an alternative approach to surface hydrologic modeling couched on the premise that the physics of watershed behavior can be captured in a meaningful way at an appropriate scale. The growing availability of digital spatial data and remote sensing imagery, along with the availability of automated approaches to data extraction and aggregation, provides the stimulus for this alternative modeling approach.

The specific objectives of this research are:

1. To develop a process-based surface hydrologic model and fully integrate the model in the ARC/INFO GIS software package.
2. To test the validity of the model in simulating the hydrologic response of an agricultural watershed.

In the study, the surface hydrologic model, developed on the basis of the kinematic wave equation, is tightly coupled with the ARC/INFO GIS to provide a watershed surface hydrologic modeling system (WSHMS). Generally, the model consists of five primary interactive component and interrelated components that include (1) overland flow modeling component that is based on the Saint Venant's equation; (2) channel flow modeling component that adopts the Manning's equation; (3) an infiltration module that uses the Green-Ampt equation; (4) a routing module; and (5) a pre- and post-processing module for preparation of input data and analysis and display of output data. In the development of these modules, use was made of the arc macro language (AML) in ARC/INFO GIS, and the pre- and post-processing module was structured according to the standard primitives found in most graphical user interfaces. An example application and implementation of WSHMS to the Walnut Creek watershed near Ames, Iowa, is described.

# 2. REVIEW OF PREVIOUS STUDY

## 2.1 Classification of Hydrologic Models

Hydrologic models may be subdivided into a number of categories based on the way they handle randomness and space-time variability of hydrologic phenomena. Figure 2.1, adapted from Chow et al. (1988), graphically illustrates the subdivision of a hydrologic model into two primary groups: stochastic and deterministic. Unlike stochastic models which incorporate randomness and generate probability functions of outputs, a deterministic model generates an output for a specific input which is considered to be singled-valued. Considering the treatment of spatial variability, hydrologic models can also be classified as spatially independent (or lumped) and spatially correlated (or distributed). In a deterministic lumped model, parameters that represent physical system processes are spatially averaged with one single value used to represent the entire modeling domain. On the other hand, instead of ignoring spatial distributed models

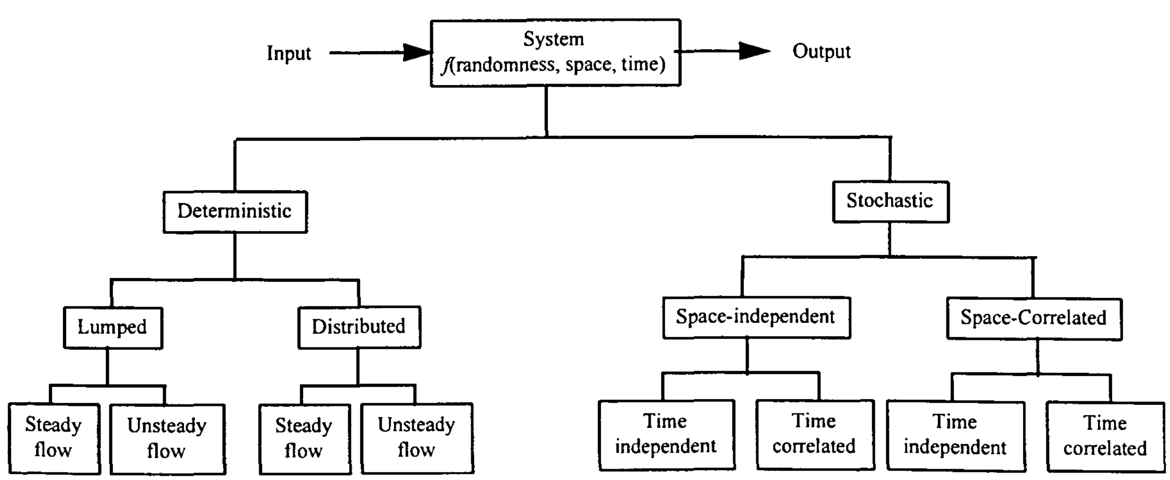


Figure 2.1 General classification of hydrologic models (adopted from Chow et al., 1988)

incorporate the heterogeneity of hydrologic parameters and the modeled domain can be divided into many computational elements (e.g. grid cells) and the hydrologic processes modeling takes place at the element level. Both the lumped and distributed models can be subdivided into time correlated (unsteady) or time independent (steady) depending on how time varying processes are presented in the model.

## 2.2 Conventional Methods of Surface Hydrologic Modeling

For some time we have had at our disposal, tools for predicting hydrologic characteristics of watershed runoff. These tools range from complex process-based equations to the simple empirical equations such as the Soil Conservation Service (currently known as the Natural Resources Conservation Service) Curve Number technique. Although the empirical technique using rainfall and runoff is widely adopted, it is not always the most desirable method since several other factors also affect the process of runoff. These factors include: precipitation characteristics, geological features, terrain, and vegetation cover, meteorological conditions, and the surface characteristics of the watershed. It is sometimes the unavailability of so much information on a watershed that has led researchers to adopt empirical modeling techniques, some of which estimate the hydrologic characteristics of a watershed using its geomorphic parameters.

Potter (1953) determined empirically a regression of peak stream discharge upon factors of topography, basin area, and rainfall for 51 basins in the Appalachian Plateau. Studies relating geomorphic parameters and runoff have been reported by Benson (1962) on small ephemeral watersheds in the west and midwest and on larger ephemeral and perennial basins in the west and northwest by Moore (1968) and Hedman (1970). Similar studies on perennial drainage basins in the central and eastern states have also been made (Wong, 1963; Brown,1971). Equations derived empirically and from regression analyses are generally easy to use, but are applicable only within areas and basin size ranges wherein the effect of landscape, lithology, vegetation, terrain and climate are similar. As Brown (1971) observed, the coefficients in these regression equations lack transferability outside the range of physical environment used to derive them.

Bagley et al. (1964) used multiple regression analysis as a method of predicting the discharge in Utah and developed relations between runoff or peak discharge and a number of geomorphic and meteorological variables. Lull et al. (1966) related the average annual and seasonal runoff and daily mean discharges at selected flow durations of 137 watersheds in the northeast United States totaling less than 100 square miles to selected climatic, topographic and land use variables. Overton (1969) used a set of nine geomorphic parameters to carry out the eigenvector analysis of geomorphic interrelations for 37 small agricultural watersheds. The parameters selected were drainage area, hypsometric integral, stream density, average slope, length-width ratio, flood plain ratio, average channel slope, relief ratio and total elevation drop.

Minshall (1960) developed a method that involved estimation storm runoff volume from rainfall pattern and antecedent rainfall, and distribution of the runoff through an adaptation of the unit hydrograph principle. This work was important because it demonstrated that the unit hydrograph was dependent upon rainfall intensity and led to the development of unit hydrograph equations involving gamma distribution (DeCoursey, 1973). Haan and Read (1970) analyzed water yield data from 13 small agricultural watersheds in Kentucky by standard multiple regression techniques. DeCoursey and Deal (1974) developed a prediction equation for mean annual discharge based on 90 storm locations in Oklahoma. They compared standard multiple regression with several alternate methods of regression using principal components.

Developments in kinematic wave theory as approximations of the continuity equations of mass and momentum have had significant impacts on surface hydrologic modeling efforts. Solomon and Gupta (1977) developed a distributed numerical model for estimating surface runoff from ungaged watersheds. Lopes (1995) developed a distributed-parameter model of watershed runoff and sediment yield. Other distributed hydrologic models have been developed by Beven (1985) and Beven and O'Connell (1982).

## 2.3 GIS-based Hydrologic Modeling

The functional components of a geographic information system (GIS) are specifically designed to efficiently store, update, manipulate, retrieve, analyze, and display all forms of geographically referenced data. The GIS technology provides users with the capability of programming their own applications using built-in functions and to run these applications through a batch or interactive interface. GIS software capabilities are useful in themselves, but combined with various kinds of simulation models they provide a robust modeling environment. Because of this enhanced visualization and display capabilities, the GIS technology has become widely used in hydrologic modeling. Also, some existing GIS softwares contain built-in functions that enhance hydrologic modeling. Because of these issues, researchers have attempted to develop linkages between GIS and hydrologic models. However, most of these linkage were developed utilize GIS as a tool for display and analysis of data input and output.

Zhang and Cundy (1989) developed a model that allows explicit incorporation of spatial variations in hillslope physical characteristics, including surface roughness, infiltration, and microtopography to simulate two dimensional overland flow without channel system component. Stuebe and Johnson (1990) incorporated the Soil Conservation Service (SCS) curve number equation into GRASS GIS to estimate runoff under different land management conditions. They concluded that using GIS significantly improved the accuracy of hydrologic modeling compared to traditional techniques. Drayton et al. (1992) also linked the SCS curve number equation with GIS and utilized remotely-sensed imagery data from satellites to generate land cover data for calculating curve number and runoff.

Further research utilizing GIS in surface hydrologic modeling has been conducted. For example, Vieux (1991) developed a finite element model for simulating surface runoff using triangular elements generated by ARC/INFO GIS. Maidment (1993a) provided a GIS-based methodology for generating unit hydrographs and surface runoff based on the linear theory of rainfall-runoff. Gao et al. (1993) linked GRASS GIS with a distributed parameter rainfall-runoff model. In their study, a two-dimensional kinematic wave equation was used to simulate overland flow while the Green-Ampt equation was employed for predicting infiltration. Julien et al. (1995) developed CASC2D that also utilizes a two-dimensional Saint-Venant equation of mass and momentum to represent the physics of overland flow. In the study, CASC2D model was tightly coupled with GRASS, a raster-based GIS software.

# 3. MATERIALS AND METHODS

## 3.1 Modeling Surface Hydrologic Processes

Surface runoff and stream flow are dependent on climate as well as the physical characteristics of the drainage basin. Climate factors include the type of precipitation, rainfall intensity, duration of rainfall, direction of storm movement, antecedent soil moisture, and other climatic conditions that affect evaporation and transpiration. The physical characteristics of watershed include land use, topography, soil type, channel type, shape, area, and artificial drainage. In a distributed hydrologic model, most of the characteristics of the watershed can be taken care simply just by using the distributed data. The hydrologic processes in surface runoff model can be subdivided into precipitation, overland flow, infiltration, evapotranspiration, channel flow, and subsurface return flow components. This study omitted the influence of evapotranspiration process and mainly focused on the influence of topography, land use and land cover, and soil distribution on the surface runoff.

### *3.1.1 Precipitation*

The intensity of precipitation varies in space and time during a rain storm. So constant rainfall intensity throughout the storm event is not sufficient in the study of developing a distributed hydrologic model. However, only limited rainfall gauge stations that can provide precipitation information can be found in the field. In order to have precipitation data on each cell in a study area, two dimensional interpolation technique must be applied to make the precipitation information available at each time step. Two of the most popular two-dimensional interpolation methods are Kriging and inverse distance interpolation (IDW). The Kriging method make more sense from the statistical analysis point of view. However, it is more computationally intensive than the IDW method. So this study adopted the IDW technique to regionalize precipitation data from rain gauge stations for the entire watershed.

The algorithm of IDW technique for regionalizing precipitation data is described below. For each cell within the study area, a weight is assigned for each precipitation station, based on the distance of the station from the cell. The estimate of rainfall intensity on a specific cell is equal to the summation of the measured rainfall intensity at each station times the associated weight. Thus:

$$P(i,j) = \sum_{k=1}^{m} \left( \frac{(1/d_k)^2}{\sum_{l=1}^{m} (1/d_l)^2} P_k \right) \tag{1}$$

where $P(i, j)$ = rainfall intensity on cell (i, j)

$d_k$ = distance of station k to cell (i, j)

$d_l$ = distance of station l to cell (i, j)

$m$ = number of the stations

$P_k$ = rainfall intensity measured by station k

### *3.1.2 Infiltration*

Literature is abound on the factors that influence infiltration. Infiltration equations can be classified into empirical, physical and theoretical categories (Maidment, 1993b). Some of these equations are briefly introduced below.

Philip (1957) developed an analytical model of the form:

$$q(t) = \frac{1}{2} S t^{-1/2} + A_2 + A_3 t^{1/2} + A_4 t + \cdots + A_n t^{n/2-1} \tag{2}$$

in which q(t) is the infiltration rate. The limitation of Philip's equation is that it is not valid for extended time periods, because the series diverges after a certain time.

Kostiakov (1932) developed an empirical equation of infiltration as:

$$f_p = K_k t^{-\alpha} \tag{3}$$

where $K_k$ and $\alpha$ are constants which depend on the soil and initial conditions

The limitations of using Kostiakov's model are it needs a set of observed infiltration data for evaluation; thus it cannot be applied to other soils and conditions which differ from the conditions for which the parameters were determined. The Kostiakov's model has primarily been used for irrigation applications.

The Horton (1940) empirical equation for infiltration is

$$f_p = f_c + (f_0 - f_c) e^{-\beta t} \tag{4}$$

where $f_p$ is the infiltration rate at time t

$f_0$ is the maximum infiltration rate at the beginning of a storm event

$f_c$ is the infiltration rate when the soil become saturated

$\beta$ is a constant

Horton's equation is applicable only when effective rainfall intensity is greater than $f_C$ and parameters $f_O, f_C$, and β must be evaluated using observed infiltration data.

Holtan (1961) infiltration equation is

$$f = a\ SA^{1.4} + f_c \tag{5}$$

where $f$ = potential infiltration rate ($LT^{-1}$)

$a$ = coefficient of surface connected porosity

$SA$ = available pore space (L)

$f_c$ = constant infiltration rate ($LT^{-1}$)

The major difficulty with the use of Holtan's equation is the evaluation of the top layer of soil. In this study, the Green-Ampt (1911) infiltration equation was used. In it's simplest form, this infiltration is expressed as:

$$f = K\left(1 + \frac{H_f M_d}{F}\right) \tag{6}$$

where f = infiltration rate [$LT^{-1}$];

K = hydraulic conductivity [$LT^{-1}$];

$H_f$ = capillary pressure head at the wetting front[L];

$M_d$ = soil moisture deficit equal to ($\theta_e$ - $\theta_i$);

$\theta_e$ = effective porosity equal to ($\phi$ - $\theta_r$);

$\phi$ = total soil porosity;

$\theta_r$ = residual saturation;

$\theta_i$ = initial soil moisture content;

F = total infiltration depth [L].

Analysis conducted by Rawls et al. (1983) concluded that soil texture has the most significant discriminator of the Green-Ampt parameters. Table 3.1 shows the relationship between soil texture class and parameters in Green-Ampt equation as suggested by Rawls et

Table 3.1 Parameters of the Green-Ampt equation for different soil textures (Rawls et al., 1983)

| Soil texture | Effective Porosity | Capillary Pressure Head (cm) | Hydraulic Conductivity (cm/hr) |
|---|---|---|---|
| Sand | 0.417 | 4.95 | 11.87 |
| Loamy sand | 0.401 | 6.13 | 2.99 |
| Sandy loam | 0.412 | 11.01 | 1.09 |
| Loam | 0.434 | 8.89 | 0.34 |
| Silt loam | 0.486 | 16.68 | 0.65 |
| Sandy clay loam | 0.33 | 21.85 | 0.15 |
| Clay loam | 0.309 | 20.88 | 0.10 |
| Silty clay loam | 0.432 | 27.3 | 0.10 |
| Sandy clay | 0.321 | 23.9 | 0.06 |
| Silty clay | 0.423 | 29.22 | 0.05 |
| Clay | 0.385 | 31.63 | 0.03 |

al. (1983). Further considerations of the influence of different types of land management, land cover, soil water content, and climate on infiltration rate can be found in the Rawls and Brakensiek (1988).

### *3.1.3 Overland Flow*

Overland flow can generally be simulated as a lumped or distributed process. However, lumped methods may be insufficient, because they have no hydraulic mechanisms to describe upstream propagation of changes in flow momentum (Chow et al., 1988). So a distributed modeling, approach was adopted in this study to simulate overland flow in catchments. The overland flow equation is based on a two-dimensional overland flow can be accomplished by using two-dimensional Saint-Venant (1871) equation. Continuity and momentum equations are the primary governing equations and are represented as

Continuity equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_x \tag{7a}$$

$$\frac{\partial Q}{\partial y} + \frac{\partial A}{\partial t} = q_y \tag{7b}$$

Momentum equation:

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g\left(S_{x0} - S_{fx}\right) = 0 \tag{8a}$$

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial y}\left(\frac{Q^2}{A}\right) + g\frac{\partial x}{\partial y} - g\left(S_{y0} - S_{fy}\right) = 0 \tag{8b}$$

*3.1.4 Channel Flow*

The flow rate in stream channels can be derived from Manning's equation which can be derived from the Darcy-Weisbach equation for head losses due to the channel friction. The Manning's equation for channel flow is

$$Q = \frac{1}{n} A R^{2/3} S_f^{\ 1/2} \tag{9}$$

where A is the cross-sectional area in ($L^2$), R is the hydraulic radius (L), $n$ is the manning roughness coefficient, $S_f$ is the friction slope and $Q$ is the flow rate ($L^3T^{-1}$). Values of n for different types of land cover were evaluated by Engman (1986) and Huggins et al. (1975) and are summarized in Table 3.2.

Table 3.2 Manning's roughness values for various field conditions

| Field condition | Range of Manning n |
|---|---|
| **Fallow** | |
| smooth, rain packed | 0.01-0.03 |
| medium, freshly disked | 0.1-0.3 |
| rough turn plowed | 0.4-0.7 |
| **Cropped** | |
| grass and pasture | 0.05-0.15 |
| clover | 0.08-0.25 |
| small grain | 0.1-0.4 |
| row crops | 0.07-0.2 |

*3.1.5 Evapotranspiration*

Several useful methods has been developed to estimate evapotranspiration. For example, Ritchie (1972) computed the potential evapotranspiration using the following relationship:

$$E_0 = \frac{1.28 H_0 \Delta}{\Delta + \gamma} \tag{10}$$

where $E_0$ is the potential evapotranspiration; Δ is the slope of the saturation vapor pressure curve at the mean air temperature; $H_0$ is the net solar radiation; and γ is the psychrometric constant. Δ is computed with the equation

$$\Delta = \frac{5304}{T^2} e^{(21.255 - 5304/T)} \tag{11}$$

where T is the daily temperature in degree kelvin. $H_0$ is calculated with the equation

$$H_0 = \frac{(1 - \lambda) R}{58.3} \tag{12}$$

where R is the daily radiation in langleys and λ is the albedo for solar radiation.

Jensen et al. (1990) showed the reference $ET_0$ (Penman, 1963) as:

$$\lambda ET_0 = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} 6.43(1.0 + 0.53 v_2)(e_s - e_d) \tag{13}$$

where $\lambda ET_0$ = reference ET for a well - watered grass expressed as latent heat flux density, MJ $m^{-2} day^{-1}$,
$\Delta$ = slope of the saturation vapor pressure curve in kPa/°C,
$\gamma$ = psychrometric constant in kPa/°C,
$R_n$ = net radiation in MJ $m^{-2} day^{-1}$,
G = heat flux density to the soil in MJ $m^{-2} day^{-1}$,
$v_2$ = average wind speed at a height of 2 m in m / s,
$e_s$ = saturated vapor pressure at mean air temperature in kPa,
$e_d$ = saturated vapor pressure at mean dew - point temperature in kPa.

The slope of the saturation vapor pressure can be obtained from:

$$\Delta = 0.20(0.00738T + 0.8072)^7 - 0.000116 \tag{14}$$

where T = mean air temperature in °C.

The psychrometric constant in kPa/°C can be derived as

$$\begin{aligned} \gamma &= 0.00163P / \lambda \\ P &= 101.3 - 0.01055 * E \\ \lambda &= 2.501 - 0.002361T \end{aligned} \tag{15}$$

where P = estimated atmospheric pressure in kPa,
E = elevation in m,
$\lambda$ = latent heat of vaporation of water in MJ / kg.

## 3.2 Watershed Surface Hydrologic Modeling System

### *3.2.1 Model Structure*

As shown in Figure 3.1, the watershed surface hydrologic modeling system or WSHMS consists of three primary modules: data pre-processing, overland flow, channel flow and user interface. The pre-processing component facilitates the acquisition and preparation of the required data layers for the model simulation. These layers include contour, digital elevation model (DEM), land slope, aspect, soils, etc. The overland flow component, as described previously, contains the equations for calculating flow depth and flow rate based on the Saint Venant's equation. The channel flow component uses Manning's equation as the governing equation and overland flow at the cells besides the channel system as the overland flow enter the stream system to the watershed outlet. Each of these modeling components are examined below.

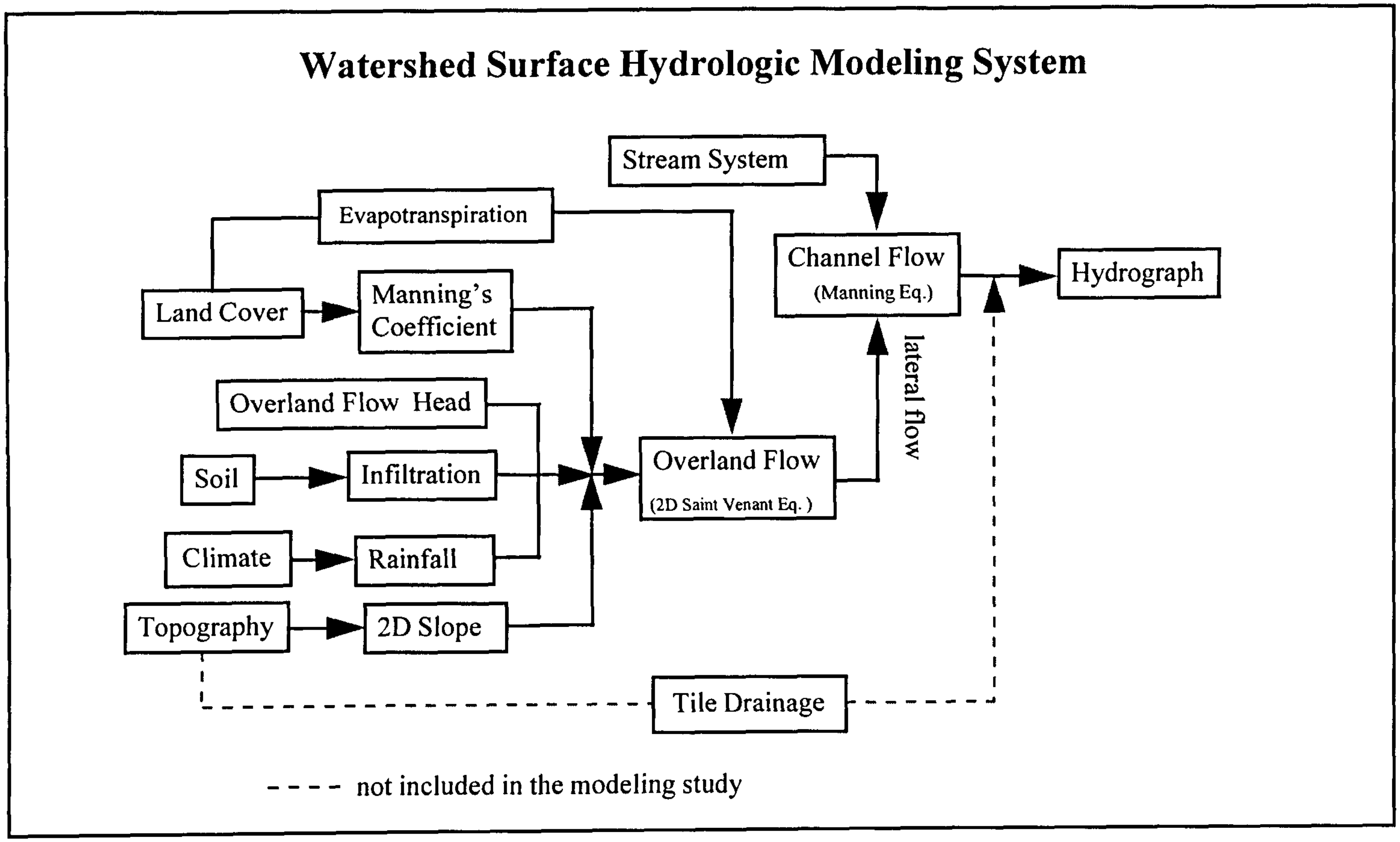


Figure 3.1 Conceptual components and structure of WSHMS

### *3.2.2 Data Preprocessing Module*

Since the model resides in a grid format, the functionality of the data preprocessing component reduces to that of generating the grid-level data layers used in the model from vector data coverages. The data layers required by the model were generated by the pre-processing component and include themes such as soils and soil properties, hydrography, land use, topography, Manning roughness coefficient, and soil infiltration parameters. These data layers were converted to the grid format for the entire watershed. The only exception is the time-variant rainfall data which was stored as an INFO table. The IDW interpolation technique described earlier was used to generate grid-cell level rainfall intensity data for each grid cell in the watershed. Figure 3.2 shows the process of incorporating rainfall intensity data generated in the grid-cell format.

### *3.2.3 Overland Flow Module*

The overland flow module, as shown in Figure 3.3, contains rainfall intensity interpolation function, grid-cell level infiltration rate calculation, and two dimensional flow rate and flow depth computation at each time step. The rain gauge stations with tabular rainfall information and geographic coordinates in the watershed were used to interpolate the rainfall intensity for the entire watershed by using the IDW technique. The Green-Ampt equation was chosen to calculate the infiltration rate and the fully explicit finite difference scheme was applied to the Green-Ampt equation to compute the infiltration rate and

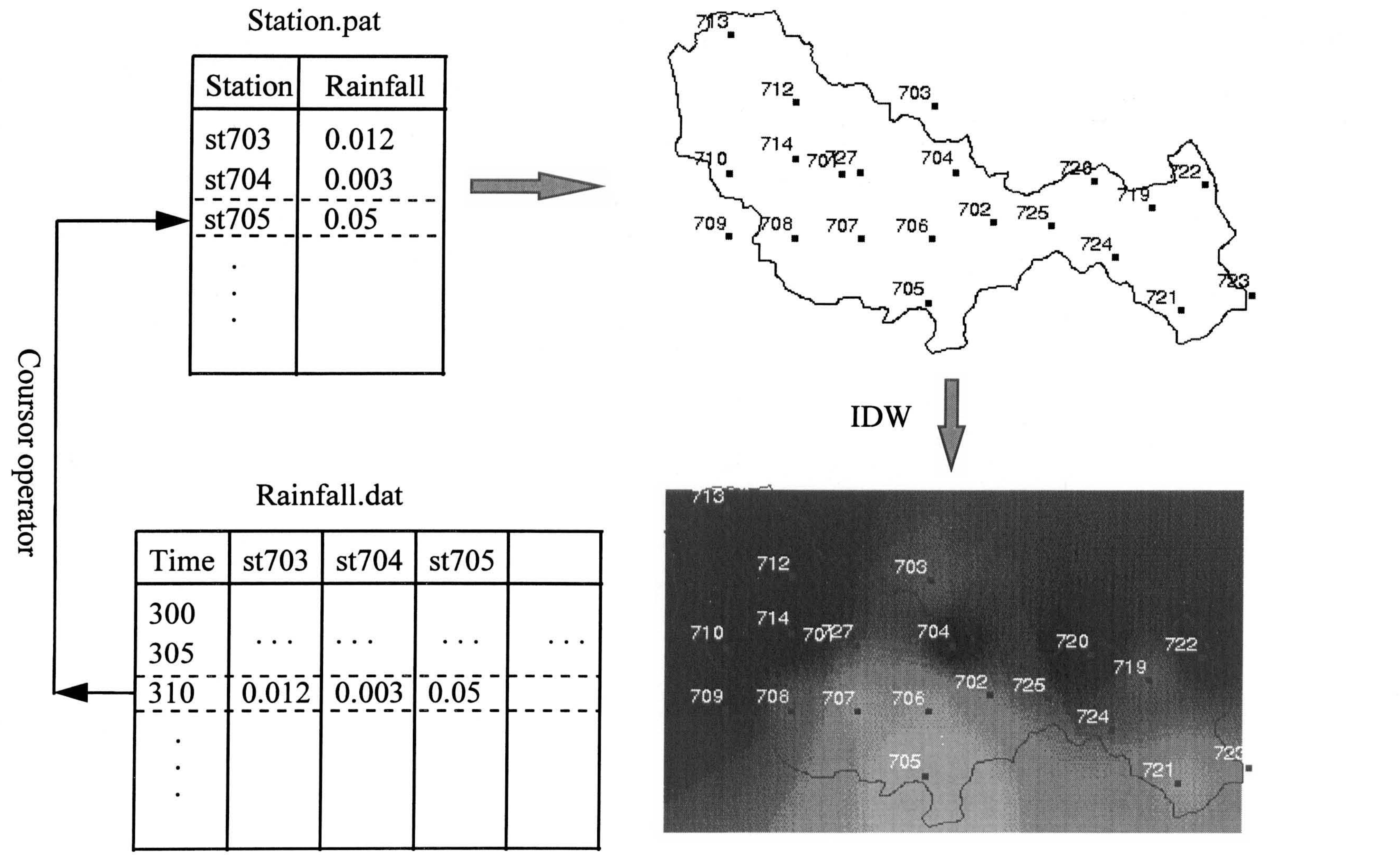


Figure 3.2 Getting rainfall information from INFO file to rain gauge station coverage and using IDW interpolation technique to generate rainfall intensity grid for any simulation time.

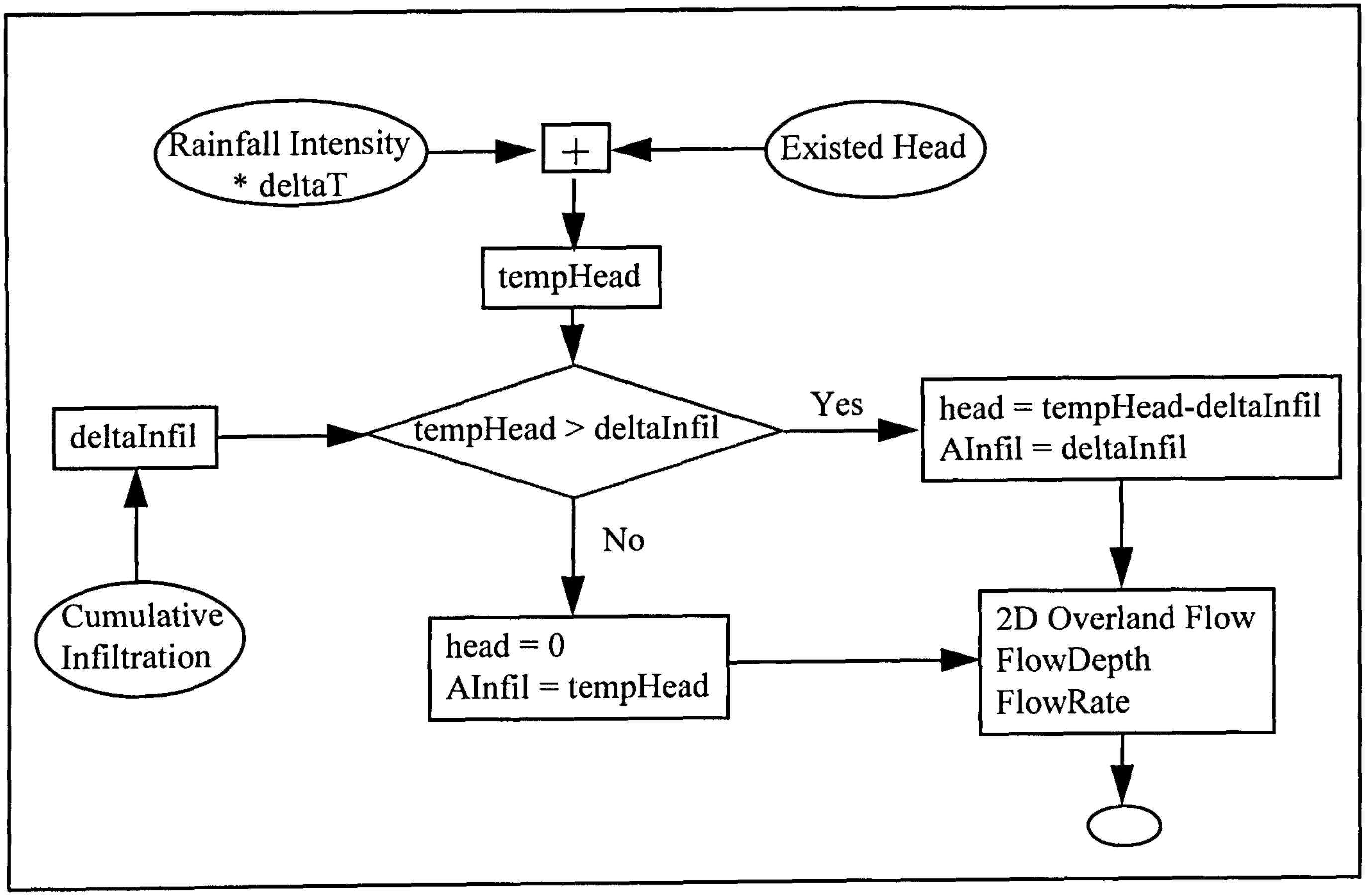


Figure 3.3 Flow chart of the overland flow module

cumulative infiltration rate through each time domain. Here the parameters of the Green-Ampt equation were obtained from a look-up table constituted by using information from Table 3.1. In developing the flow equation in general, the assumptions made were: (a) the influence of tile drainage to the simulated hydrograph is neglected, (b) evapotranspiration is not considered, and (c) contribution to channel flow from groundwater sources are neglected. Although these assumptions are very limiting in practice, making them facilitate the integration of the equations with the GIS.

The overland flow depth and flow rate were calculated using a two dimensional form of the Saint Venant's equation for overland flow. This equation can be expressed in integro-differential form as:

$$\frac{d}{dt}\iiint_{C.V.}\rho d\forall + \iint_{C.S.}\rho V dA = 0 \tag{16}$$

Converting equation (16) into a partial differential form yields

$$\frac{d}{dt}(\rho Ah) + (V_x\rho yh + V_y\rho yh + \frac{\partial V_x}{\partial x}x\rho yh + \frac{\partial V_y}{\partial y}y\rho xh) - (V_x\rho yh + V_y\rho yh + ixy) = 0 \tag{17}$$

Substituting for $A = xy$ in Equation (17) yields

$$\rho xy\frac{dh}{dt} + \frac{\partial V_x}{\partial x}x\rho yh + \frac{\partial V_y}{\partial y}y\rho xh - ixy = 0$$

Upon simplification one obtains

$$\frac{dh}{dt} + \frac{\partial V_x}{\partial x}h + \frac{\partial V_y}{\partial y}h = i \tag{18a}$$

$$\frac{dh}{dt} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = i \tag{18b}$$

in which $q_x (= V_x * h)$ and $q_y (= V_y * h)$ are the x and y components of the dscharge per unit width.

In the finite difference scheme, Equation (18b) can be expressed as

$$h(j,k,t+\Delta t) = h(j,k,t) + i\Delta t - \left( \frac{q_x(j,k,j,k+1,t) - q_x(j,k-1,j,k,t)}{w} - \frac{q_y(j,k,j+1,k,t) - q_y(j-1,k,j,k,t)}{w} \right) \Delta t \tag{19}$$

where w is the elemental (grid-cell) width. The diffusive wave approximation of the momentum equation in the x-direction and y-direction are, respectively:

$$S_{fx} = S_{fx0} - \frac{\partial h}{\partial x} \tag{20a}$$

in which

$$S_{fx}(j,k-1,j,k,t) = S_{fx0}(j,k-1,j,k) - \frac{h(j,k,t) - h(j,k-1,t)}{w} \tag{20b}$$

$$S_{fx0}(j,k-1,j,k) = \frac{Elev(j,k-1) - Elev(j,k)}{w} \tag{20c}$$

Similarly,

$$S_{fy} = S_{fy0} - \frac{\partial h}{\partial y} \tag{21a}$$

$$S_{fy}(j-1,k,j,k,t) = S_{fy0}(j-1,k,j,k) - \frac{h(j,k,t) - h(j-1,k,t)}{w} \tag{21b}$$

$$S_{fy0}(j-1,k,j,k) = \frac{Elev(j-1,k) - Elev(j,k)}{w} \tag{21c}$$

in which Elev(j,k) is the elevation value at the center of grid cell (j,k) and other terms are as previously defined. The kinematic wave approximation requires the local discharge to be some unique function of the amount of water stored per unit area. Thus, the discharge-depth relationship can be expressed as:

$$q_x = \alpha_x h^\beta \tag{22a}$$

$$q_y = \alpha_y h^\beta \tag{22b}$$

in $\alpha_x$ and $\alpha_y$ vary with the derivative of depth in diffusive formulation, and β is a constant. Generally $\alpha_x$, $\alpha_y$, and β depend on flow regime - i.e., laminar or turbulent. For turbulent flow over a rough surface, these parameters can be derived from the Manning resistance equation (expressed in SI units), thus:

$$\alpha_x = \frac{S_{fx}^{1/2}}{n} \tag{23a}$$

$$\alpha_y = \frac{S_{fy}^{1/2}}{n} \tag{23b}$$

$$\beta = \frac{5}{3} \tag{23c}$$

As shown in Equation 23, β remains constant while $\alpha_x$ and $\alpha_y$ vary for a specific rainfall event since $S_{fx}$ and $S_{fy}$ vary. The Manning resistance equation in two-dimensions can be expressed as follows.

For $S_{fx}(j,k-1,j,k,t) \geq 0$

$$q_x(j,k-1,j,k) = \frac{1}{n(j,k-1)}\left[h(j,k-1,t)\right]^{5/3}\left[S_{fx}(j,k-1,j,k,t)\right]^{1/2} \tag{24a}$$

Otherwise for $S_{fx}(j,k-1,j,k,t) < 0$, the equation reduces to

$$q_x(j,k-1,j,k) = \frac{-1}{n(j,k)}\left[h(j,k-1,t)\right]^{5/3}\left[-S_{fx}(j,k-1,j,k,t)\right]^{1/2} \quad (24b)$$

For $S_{fy}(j-1,k,j,k,t) \geq 0$

$$q_y(j-1,k,j,k) = \frac{1}{n(j-1,k)}\left[h(j-1,k,t)\right]^{5/3}\left[S_{fy}(j-1,k,j,k,t)\right]^{1/2} \quad (24c)$$

Otherwise for $S_{fy}(j-1,k,j,k,t) < 0$

$$q_y(j-1,k,j,k) = \frac{-1}{n(j,k)}\left[h(j-1,k,t)\right]^{5/3}\left[-S_{fy}(j-1,k,j,k,t)\right]^{1/2} \quad (24d)$$

In Equation (24), using friction slope condition to determine the flow direction accounts for the backwater effect whenever the bed slope and friction slope have opposite values.

### *3.2.4 Channel Flow Module*

In WSHMS, channel flow is represented by the kinematic wave approximation to the unsteady state gradually varied flow. The continuity equation for channel flow with distributed lateral inflow is expressed as:

$$\frac{\partial A_x}{\partial t} + \frac{\partial Q}{\partial x} = q(x,t) + i(t) \quad (25)$$

in which $q(x,t)$ is the lateral flow per unit of the channel, $A_x$ is the cross-sectional area of channel, $Q$ is the channel discharge, and $i(t)$ is the influx into the channel at time t. A finite difference scheme for Equation (25) can be derived as follows:

$$\frac{A_x(t+\Delta t/2) - A_x(t-\Delta t/2)}{\Delta t} + \frac{Q_{x+\Delta x/2}(t) - Q_{x-\Delta x/2}(t)}{\Delta x} = q_x(t) + i(t) \quad (26)$$

$$A_x(t+\Delta t/2) = A_x(t-\Delta t/2) - \frac{Q_{x+\Delta x/2}(t) - Q_{x-\Delta x/2}(t)}{\Delta x}\Delta t + q_x(t)\Delta t + i(t)\Delta t \tag{27}$$

$$A_x(t_2) = A_x(t_1) - \frac{Q_{x_2}(t) - Q_{x_1}(t)}{\Delta x}\Delta t + q_x(t)\Delta t + i(t)\Delta t \tag{28}$$

in which $\Delta t = t_2 - t_1$, $t_1 = t - \Delta t/2$, $t_2 = t + \Delta t/2$; and
$\Delta x = x_2 - x_1$, $x_1 = x - \Delta x/2$, $x_2 = x + \Delta x/2$

The kinematic wave relationship can be expressed in terms of channel discharge and the cross-sectional area according to the Manning equation:

$$Q_x(t) = \frac{1}{n}A_x(t)R(t)^{2/3}S_f(t)^{1/2} \tag{29}$$

in which *R(t)* is the hydraulic radius of the channel. Assuming a rectangle channel, the relationship between cross-sectional area $A$, the hydraulic radius $R$, bottom width b, and the flow depth d at time t can be derived as:

$$d(t) = \frac{A_x(t)}{b} \tag{30}$$

$$R(t) = \frac{A_x(t)}{2d(t)+b} \tag{31}$$

For a trapezoidal channel, a similar relationship yields the following:

$$A_x(t) = d(t)b + d^2(t)z \tag{32}$$

$$d(t) = \frac{-b+\sqrt{b^2+4zA_x(t)}}{2z} \tag{33}$$

$$R(t) = \frac{A_x(t)}{2\sqrt{z^2+1}d(t)+b} \tag{34}$$

Generally,

$$S_f(t) = S_x - \frac{d_{x_2}(t) - d_{x_1}(t)}{\Delta x} \tag{35}$$

The solution to the equations discussed above were obtained by using a model fully-explicit finite difference method with a conditionally stable scheme through the temporal domain. The Courant condition (Courant and Friedrichs, 1948) was used to ensure the convergence of the model during each iteration. For the kinematic wave equations, the Courant condition was

$$\Delta t \le \Delta x_i / c_k \tag{36}$$

where $c_k$ is the kinematic wave celerity and $\Delta x_i$ is the wave travel distance. If $\Delta t$ is large such that the Courant condition is not satisfied, then there is, in effect, an accumulation of water. In this model, the utilization of Courant condition was simply a criterion based on the highest flow velocity in the channel at each iteration to determine an optimum iteration time step.

### *3.2.5 Evapotranspiration*

Jensen's (1990) version of Penman equation is chosen as evapotranspiration component in this study. However, the evapotranspiration is calculated outside the program and assigned a constant value for the specific simulation storm event.

### *3.2.6 User Interface*

All the modeling components described above were programmed using the arc macro language in ARC/INFO GIS in conjunction with the analytical functions and operations in the ARC/INFO package. To facilitate user navigation of the modeling system, a graphical user interface (GUI) based on X-windows, icons, mouse, and pointers (WIMP) was developed. The GUI for the system developed in this study is shown in Figure 3.4 to Figure 3.8. In Figure 3.4, the main menu of the system is shown. The preferred workspace provides the user freedom to choose a specific directory for modeling. In the main menu, four primary options are provided. The first option provides an environment for data preprocessing and is designed primarily to facilitate the preparation and organization of data required by the model (see Figure 3.5). The second menu option as summarized in Figure 3.6 enables the user to set-up the initial conditions (e.g., channel type, initial channel flow) for model simulation. The third menu option (Figure 3.7) facilitated simulation modeling using WSHMS for a new set of conditions. Finally, Figure 3.8 shows the menu that the user can interact with to import an existing set of data for simulation modeling.

## 3.3 System Implementation

This section provides the description of the implementation of WSHMS, detailing a step-by-step approach for the user navigation of the modeling system. Generally, users can navigate the entire modeling system by appropriately selecting options from each menu.

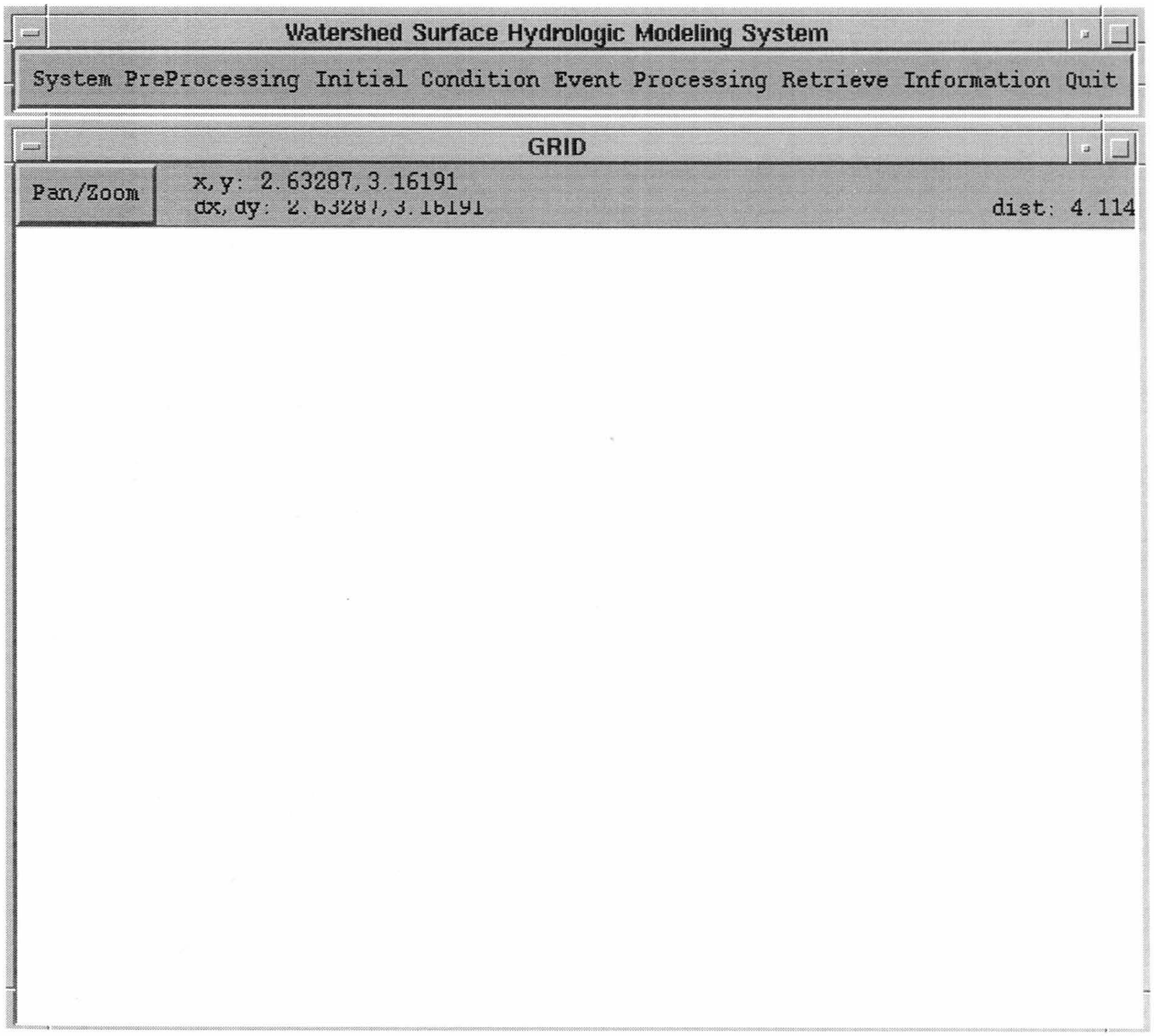


Figure 3.4 Main menu of WSHMS

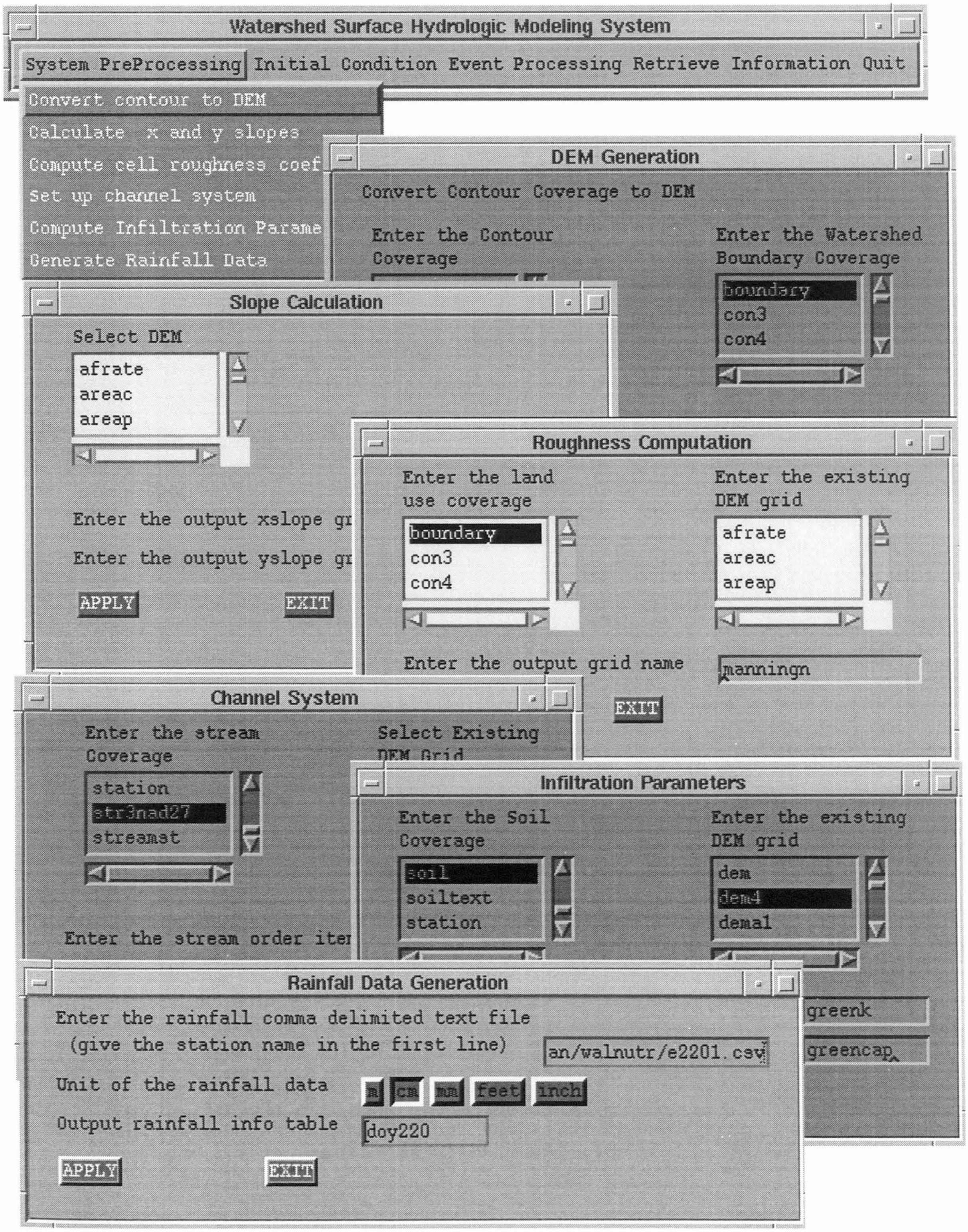


Figure 3.5 Data preprocessing module in WSHMS

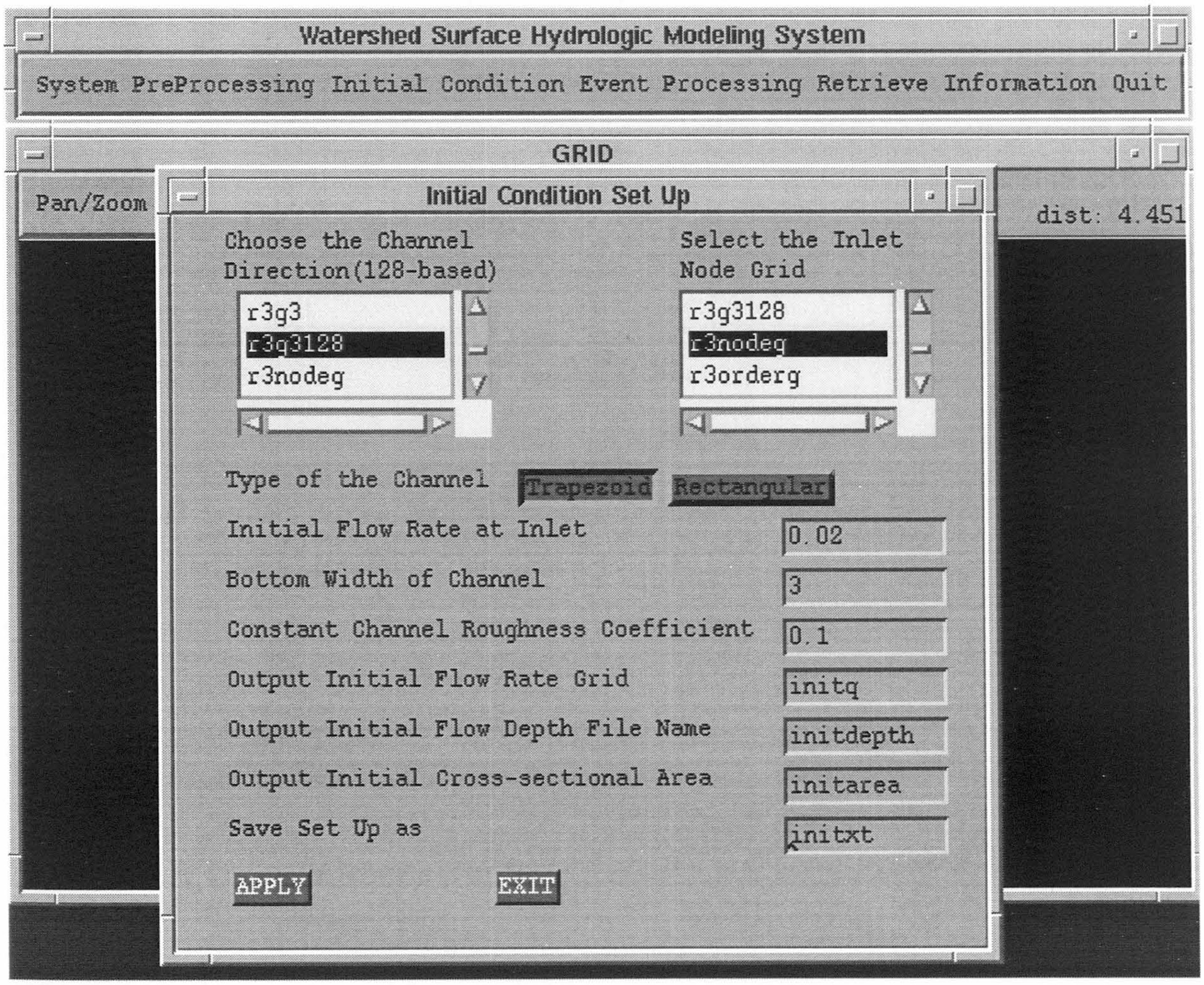


Figure 3.6 Menu for setting up initial conditions for WSHMS

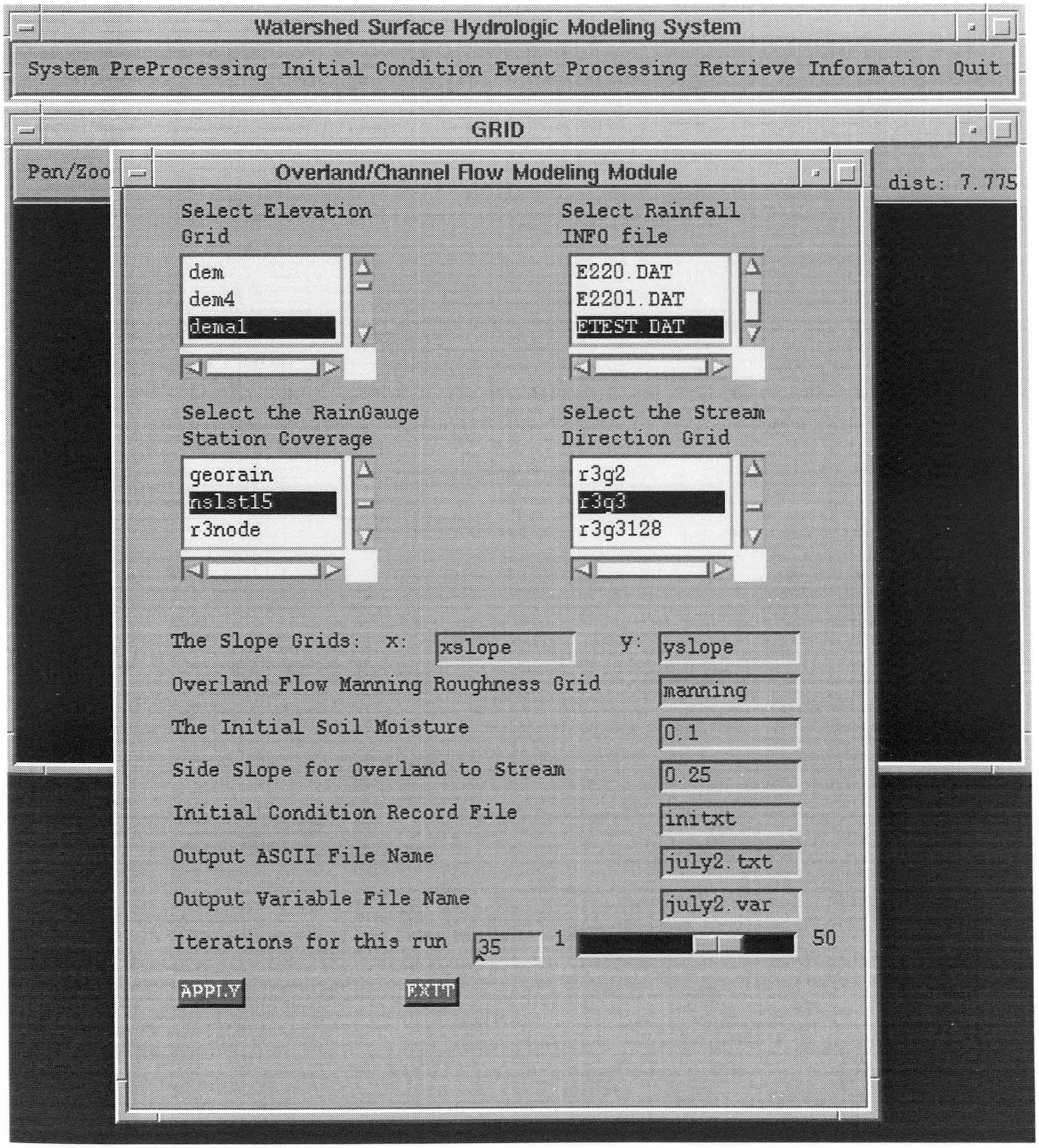


Figure 3.7 Menu for WSHMS surface runoff simulation

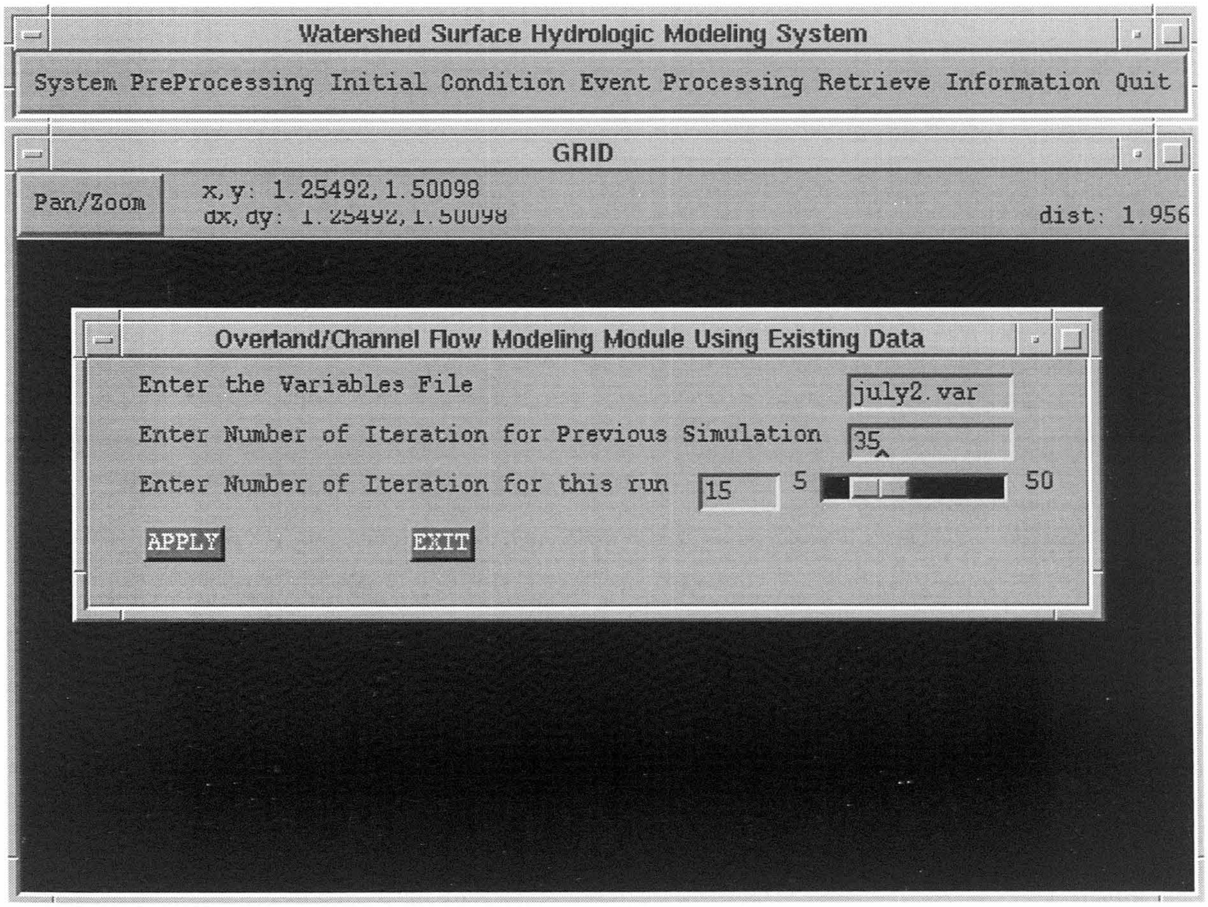


Figure 3.8 Retrieval of an existing model simulation

Table 3.3 summarizes the major steps to accomplish a surface hydrologic model simulation using WSHMS. The user begins modeling by opening and running the GRID module of ARC/INFO GIS software package. Then a modeling start-up command **wshms** is issued at the **grid:** prompt. At this point the user is asked to enter the preferred workspace for storing and retrieving data. The main menu shown in Figure 3.4 appears on the computer screen after the user clicks on "APPLY". Then the user begins by pointing and selecting **Convert contour to DEM** from **System Preprocessing** menu (Figure 3.9) to generate a DEM for the study area. Figure 3.10 shows the **DEM Generation** pop-up menu requesting the data required for processing. After entry or selection of the required data, the user then clicks "APPLY" button to proceed with processing of the contour coverage to DEM coverage. Upon generating the various grid-cell coverages within the **System Preprocessing Menu**, the user then turns attention to setting the initial conditions for the simulation by clicking on the **Initial Conditions** icon on WSHMS main menu. In the initial condition module, the user is required to provide site-specific information on channel type, initial channel flow rate, channel bottom width, and the output grid and output file names.

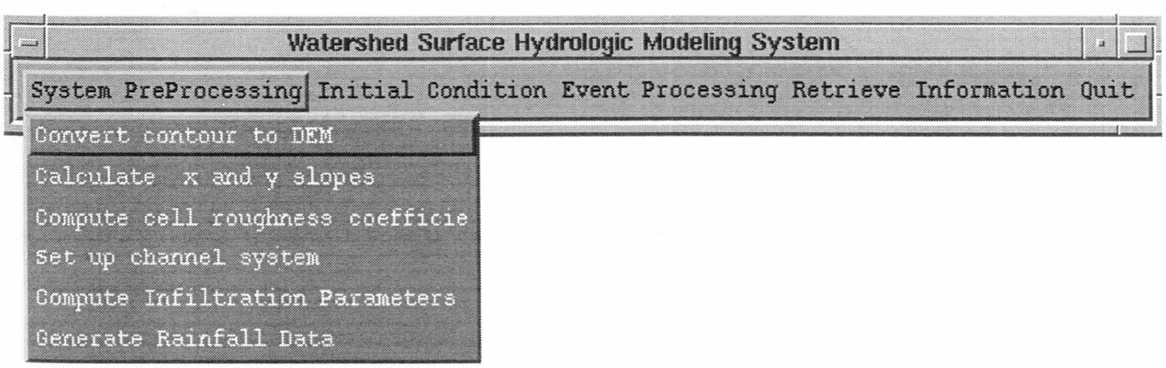


Figure 3.9 Selecting "**Convert contour to DEM**" submenu from "**System Preprocessing**" menu.

Table 3.3 Steps in the implementation of WSHMS

**Start Up**

a. At UNIX prompt (%), type **arc** to start an arc/info session.
b. At arc prompt (arc:), type **grid** to activate grid subsystem.
c. At grid prompt (grid:), type **&r wshms.aml** to start the application.
d. Enter the preferred workspace name where the data sets were stored and will be stored.
e. Click on the **APPLY** button.
The WSHMS main menu and a display window will appear on the computer screen.

**Data Preprocessing Module**

1. DEM Generation
a. Click on "**System Preprocessing**" icon and choose the "**Convert Contour to DEM**".
b. Select the contour coverage from pull-down menu in the **DEM Generation** option window.
c. Select the boundary coverage which is used to clip the DEM from pull-down menu in the **DEM Generation** window.
d. Enter the size of the grid cell.
e. Enter the name of the output DEM file name.
f. Click on the **APPLY** button.

2. Slope Calculation
a. Click on " **System Preprocessing**" icon and choose "**Calculate x and y Slopes**".
b. Select the DEM grid from pull-down menu in the **Slope Calculation** window.
c. Enter the name of x direction slope grid.
d. Enter the name of y direction slope grid.
e. Click on the **APPLY** button.

3. Calculation of Manning Roughness
a. Click on " **System Preprocessing**" and choose "**Compute cell roughness coefficient**".
b. Select the land use coverage from pull-down menu in the **Roughness Computation** window.
c. Select the existing DEM (which is used to provide information on watershed boundary and cell size of the grid) from pull-down menu in the **Roughness Computation** window.
d. Enter the name of the output roughness grid.
e. Click on the **APPLY** button.

4. Channel System
a. Click on " **System Preprocessing**" icon and choose "**Set Up Channel System**".
b. Select the stream coverage from pull-down menu in the **Channel System** window.
c. Select the existing DEM (which is used to provide information on watershed boundary and cell size of the grid) from pull-down menu in the **Channel System** window.
d. Enter the item name in the stream coverage which will be used as the stream order
e. Enter the name of the output stream system grid.
f. Click on the **APPLY** button.

5. Infiltration Parameters
a. Click on " **System Preprocessing**" and choose "**Compute Infiltration Parameters**".
b. Select the soil coverage from pull-down menu in the **Infiltration Parameters** window.
c. Select the existing DEM (which is used to give information on watershed boundary and cell size of the grid) from pull-down menu in the **Infiltration Parameters** window.
d. Enter the name for the output hydraulic conductivity grid.
e. Enter the name of the output capillary pressure head grid.
Click on the **APPLY** button.

Table 3.3 (continued)

6. Rainfall Data Generation

a. Click on " **System Preprocessing**" and choose "**Generate Rainfall Data**".
b. Enter the name rainfall *comma delimited* text file that includes the name of station in the first line.
c. Select the data unit from the choice menu.
d. Enter the name of output INFO table.
e. Click on the **APPLY** button.

**Initial Conditions Set Up Module**

a. Click on " **Initial Condition**" in the WSHMS main menu.
b. Select the 128-based channel direction grid from pull-down menu in the **Initial Condition Set Up** window.
c. Select the inlet node grid from pull-down menu in the **Initial Condition Set Up** window.
d. Choose the channel type from the choice widget.
e. Enter the initial flow rate at inlet node.
f. Enter bottom width of the channel.
g. Enter a constant Manning's roughness coefficient for the channel.
h. Enter the name for output initial flow rate grid.
i. Enter the name for output initial flow depth grid.
j. Enter the name for output initial cross-sectional area grid.
k. Enter the text file name to save the initial conditions.
l. Click on the **APPLY** button.

**Event Processing Module**

a. Click on " **Event Processing**" in the WSHMS main menu.
b. Select the elevation grid from pull-down menu in the **Event processing** window.
c. Select the rainfall INFO table from pull-down menu in the **Event processing** window.
d. Select the rainfall gauge station coverage from pull-down menu in the **Event processing** window.
e. Select the stream direction grid from pull-down menu in the **Event processing** window.
f. Enter the x and y direction slope grids.
g. Enter the Manning roughness grid for overland flow.
h. Enter the initial soil moisture value.
i. Enter the slope for overland flow to stream.
j. Enter initial condition record file.
k. Enter the name for output flow rates at stream gauge stations.
l. Enter the name to store the variable setup for use in the retrieval step.
m. Specify the number of iterations for the simulation in this run from the slider widget.
n. Click on the **APPLY** button.
   The simulation is working at this moment. The user may continue and extend the simulation by doing **event retrieval.**

**Event Retrieval Module**

a. Enter the filename where the setup variables was stored.
b. Enter the number of iterations that have been done previously.
c. Specify the number of iterations for the simulation in this run from the slider widget.
   Click on the **APPLY** button.

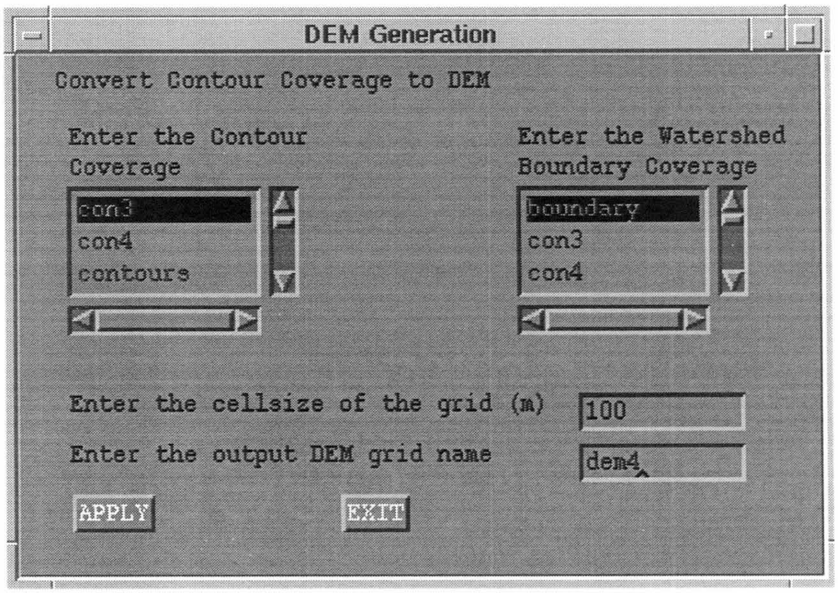

Figure 3.10 DEM generation menu in WSHMS

Upon completion of data preprocessing and the setting of initial conditions, the user is then ready to perform simulation runs, by clicking on the **Event Processing** option in the main menu. Figure 3.11 shows the data requirements and options in the **Event Processing** menu. The user's specification of the pertinent data and information required in this module and then clicking the "APPLY" button, model simulation begins.

The output ASCII file can be imported into any graphics package to plot the predicted runoff hydrograph for each gauge station based on the parameter selections. If the simulation time is not long enough, the user can use the **Event Retrieval Module** ( see Figure 3.12) to retrieve existing set of simulation data and extend the simulation to a desired time duration. After completion of the simulation modeling, the user can return to the main menu and exit WSHMS by clicking on the "EXIT" icon.

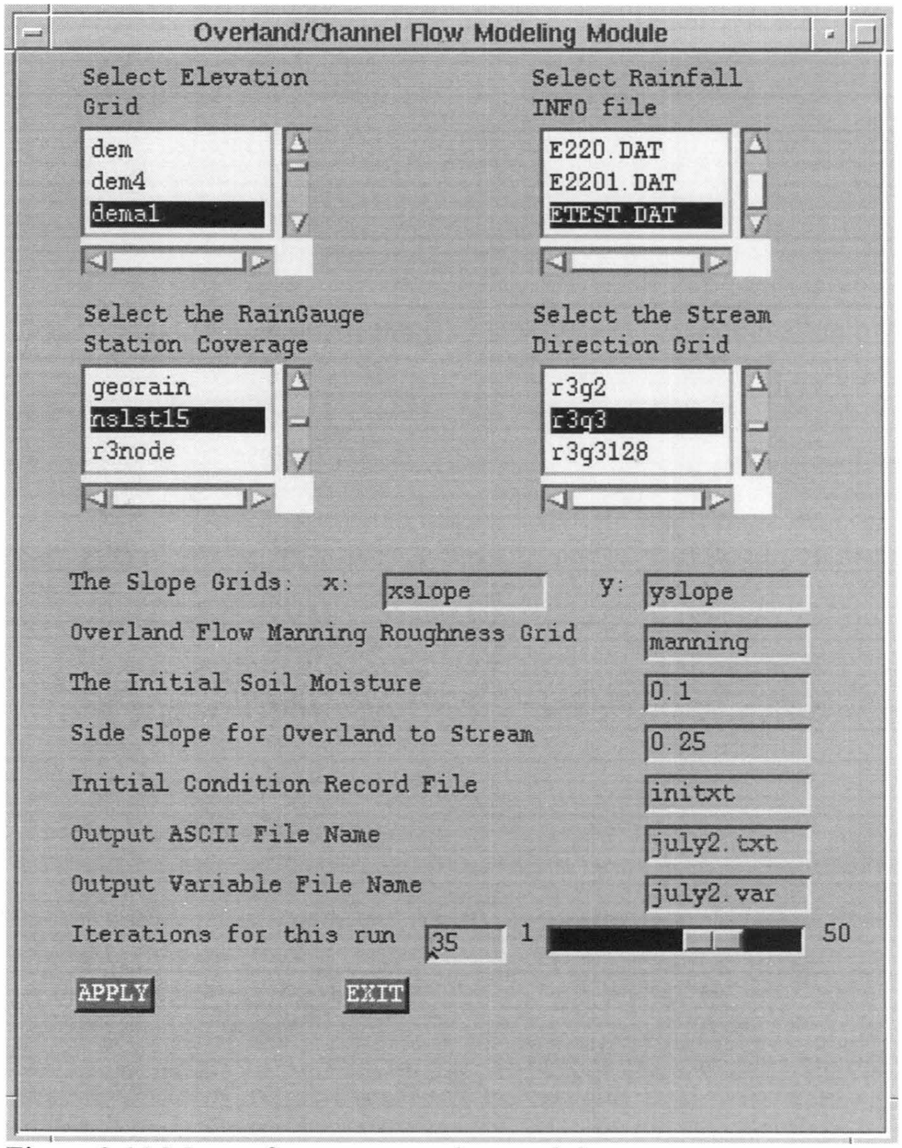


Figure 3.11 Menu of event processing module

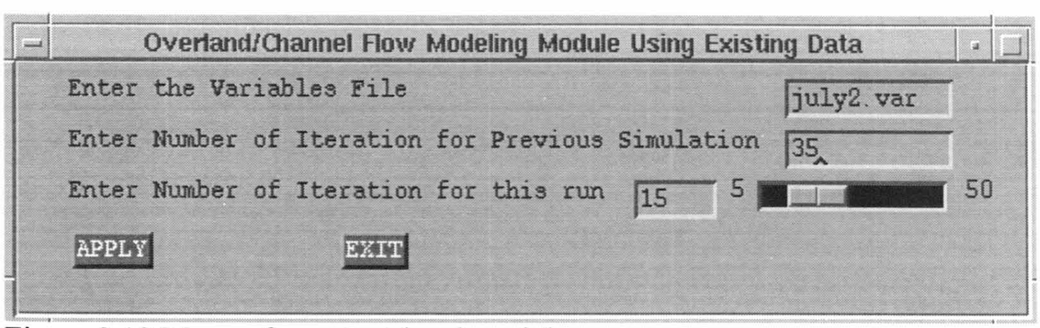


Figure 3.12 Menu of event retrieval module

## 3.4 Example Application

### *3.4.1 Description of Study Area*

To demonstrate the potential application of WSHMS, an example case study was designed. The following section provide a brief description of the study area and the results of the hydrologic modeling obtained. I would like to emphasize that the primary intent of this study was to develop a fully integrated surface hydrologic modeling system and not to extensively test the applicability of the system in several real-world applications. To test the applicability of WSHMS, the Walnut Creek watershed located near Ames was chosen as study area. The Walnut caverns approximately 5,600 hectares (or 13,837 acres) and is situated between 41° 55' N latitude to 42°00' N latitude and 93° 32' W longitude. The watershed is oriented in the east-west, direction with stream flow draining to the east of the watershed. Generally, the watershed is characterized by low relief and poor natural surface drainage, with altitude ranging from 259 meters to 320 meters. The upper 75% of the watershed area is relatively flat, while the lower 25% has more gently rolling topography (Figure 3.13). Drainage from the watershed eventually enters the south Skunk river (Schmitz, 1994), and the hydrologic conditions are determined primarily by the climatic conditions of the region.

Major climatic conditions affecting the hydrology are precipitation, temperature, wind speed and directory, relative humidity, and radiation. In additions to these, physical characteristics such as topography, soils, land use and land cover, drainage network, and geology also determine the watershed hydrologic patterns. Overall, the hydrologic response

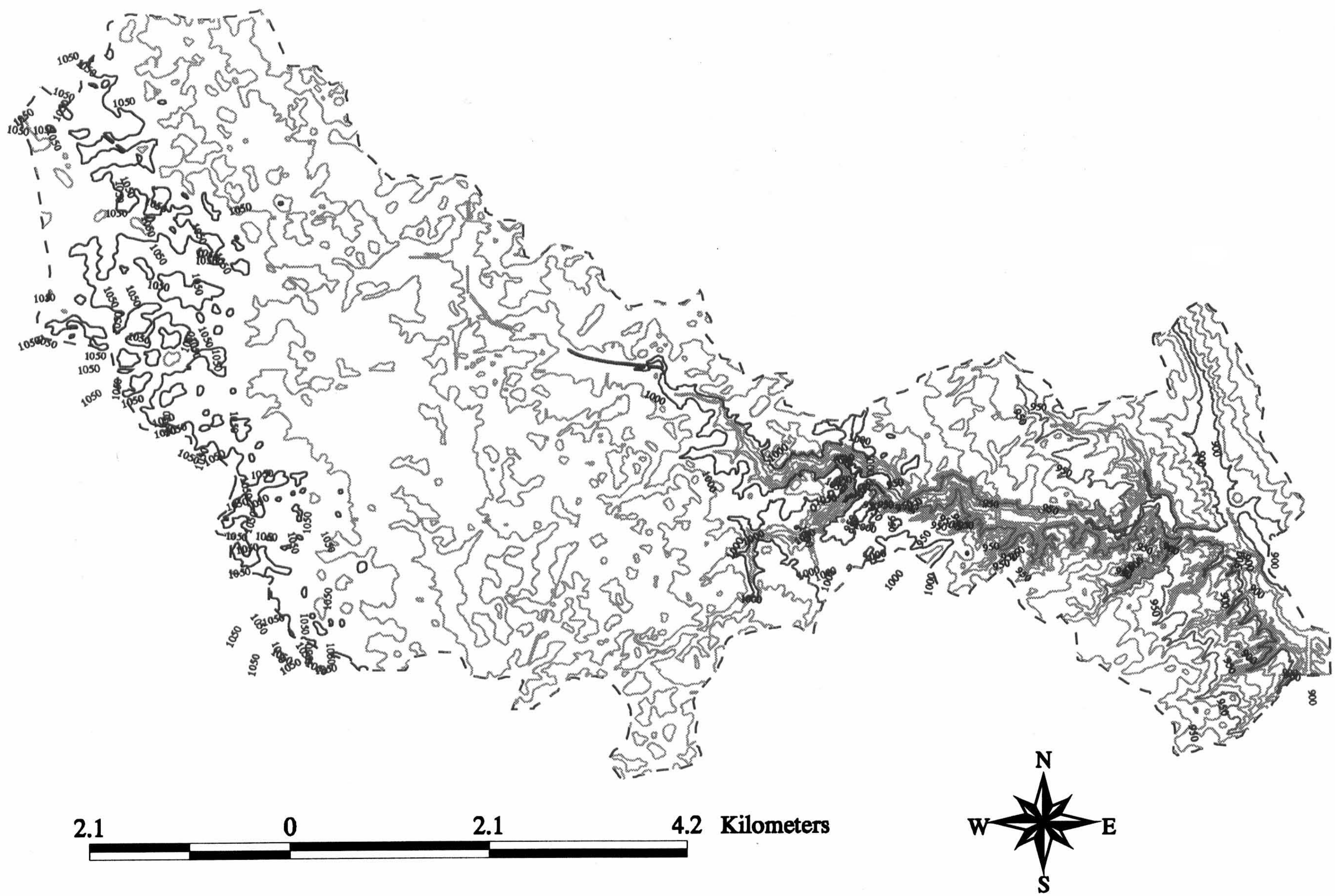


Figure 3.13 Contour map of the Walnut Creek watershed

of the watershed is influenced to a large extent by human activity, particularly land drainage networks, land management.

Land use in the watershed is dominated by row crop cultivation with over 95% of the land in a corn-soybean rotation (Keck, 1994). Land areas not used for agriculture is under pasture, woodland and residential (Figure 3.14). In the lower quarter of the watershed, which has a more rolling topography, there is an even distributed or "mix" of row crops, pasture and woodland. In contrast, the upper 75% of the watershed which is relatively flat is almost entirely under row crop production. The dominant tillage practice is the conventional type, even though management practices that include no tillage have recently been adapted. The watershed is drained by an extensive tile drainage network. Most of these tile lines are in the western, poorly drained area of the watershed. In some areas with poorly drained soils, some farmers have installed tile intakes that collect surface runoff and discharge directly into the subsurface drain (Figure 3.15).

Soils in the watershed are predominated by the Clarion-Nicollet-Webster association formed on late Wisconsin drift (Figure 3.16). Most of these soils were formed predominately in calcareous glacial till deposited in the Des Moines Lobe during the Wisconsin glaciation. Within this soil association, the primary soils consists of well drained Clarion soils located on higher or sloping areas; somewhat poorly drained Nicollet soils located on convex side slopes; Canisteo and Webster soils located on poorly drained low areas and drainageways, and very poorly drained; and Okoboji and Harps soils located in depressional areas. Permeability of most these soils allows for relatively rapid vertical


Figure 3.14 Land use and land cover layer

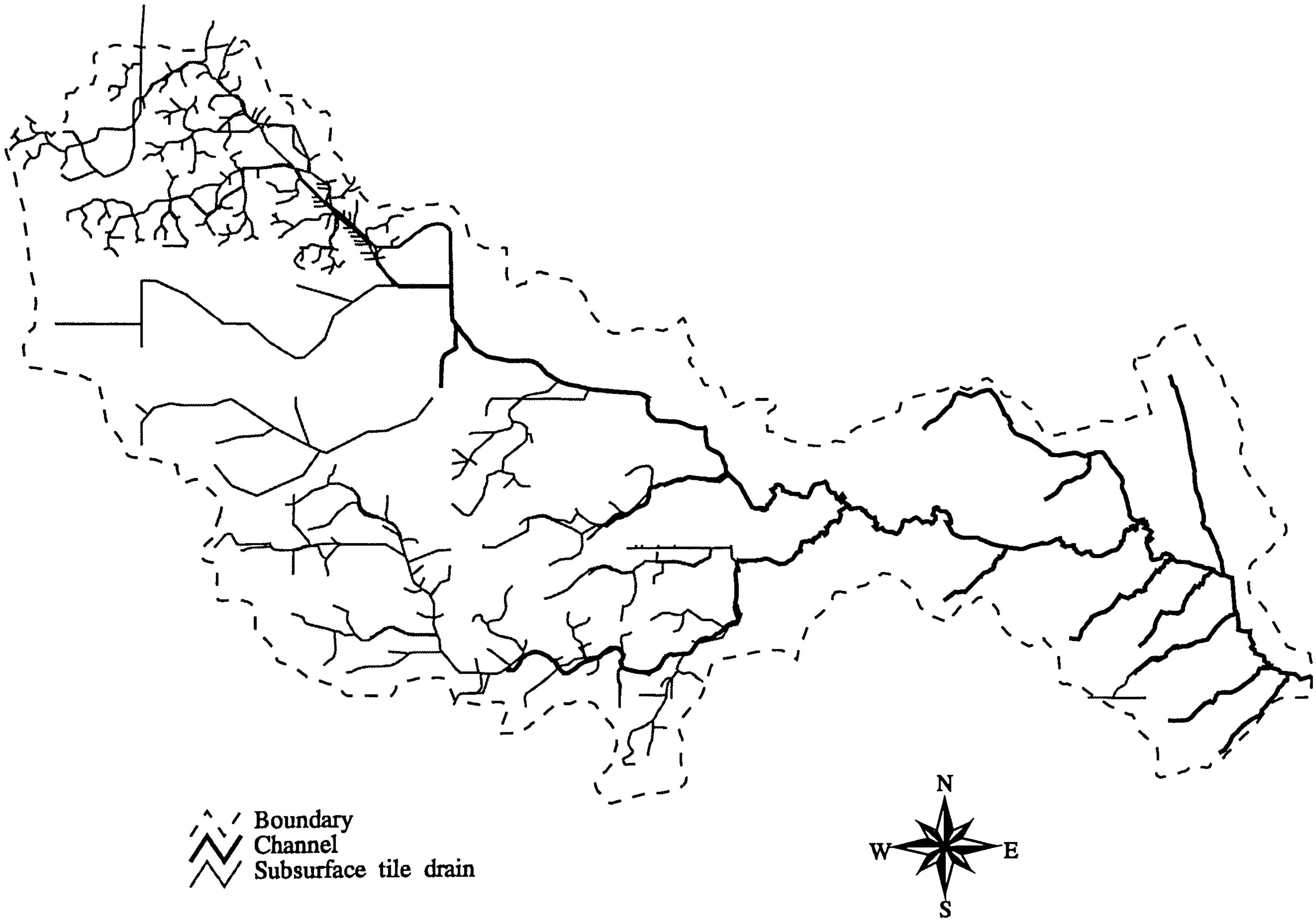


Figure3.15 Drainage system in the Walnut Creek watershed

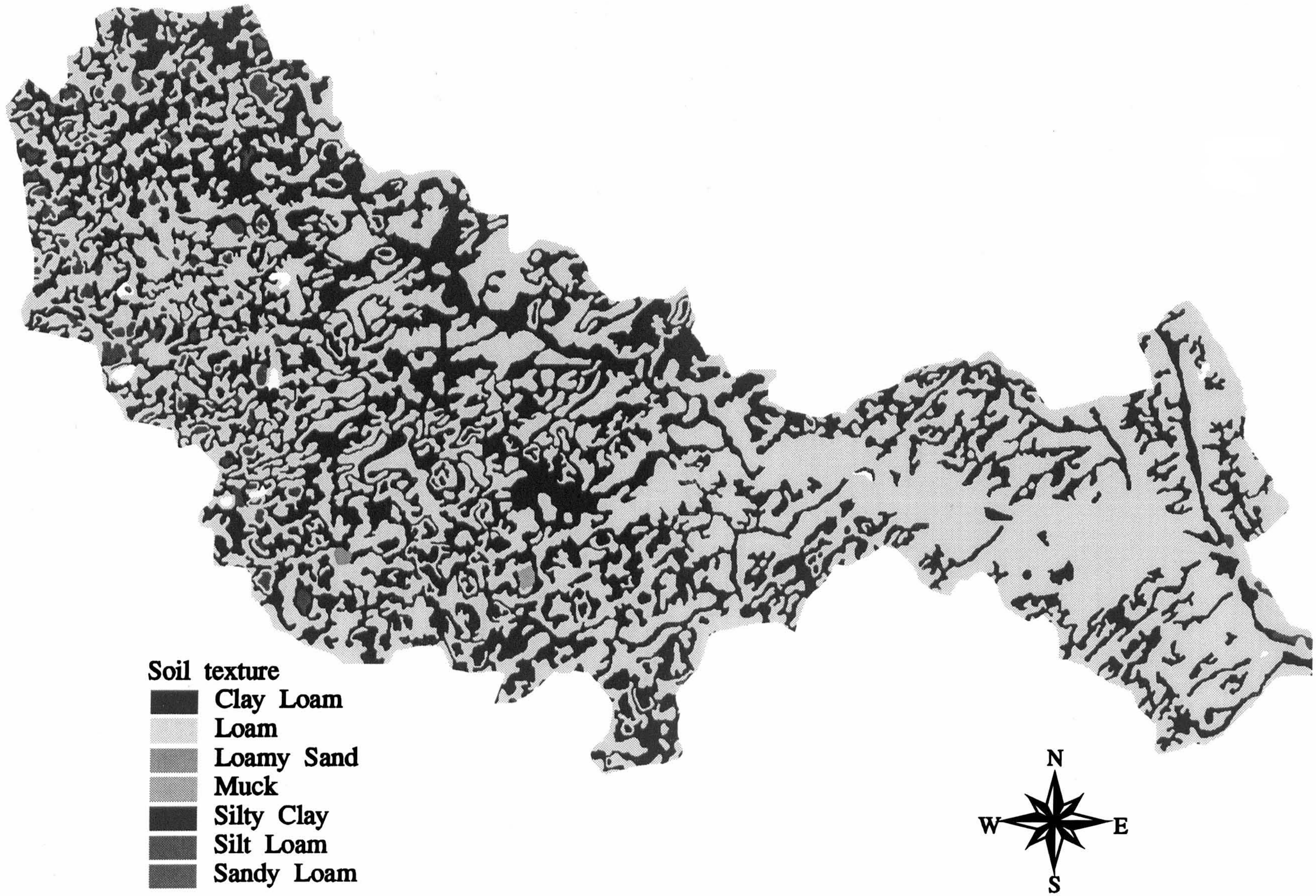


Figure 3.16 Soil texture distribution in the Walnut Creek watershed

drainage although horizontal drainage is limited to local depressions under natural conditions. The characteristics of flat topography in the west part of the watershed made the drainage tile become a important part of the flow routing in the watershed besides the natural channel (Figure 3.15).

The Walnut Creek watershed has been monitored since 1990 with weekly stream flow sampling as well as monitoring of meteorological variables conducted since 1991 (Keek, 1994). In this study, 15 rain gauge stations (Figure 3.17) were used to provide the rainfall data, while data collected at two primary gauging stations were used in the runoff evaluation.

*3.4.2 Rainfall Intensity Data*

Two rainfall or storm events which occurred in the summer of 1992 were chosen for analysis by the model. The first storm event which occurred on Julian day 197 lasted for about one hour. The five-minute rainfall accumulation data for this storm event is summarized in Table 3.4. The second storm event occurred on Julian day 220 and its corresponding five-minute rainfall accumulation data is shown in Table 3.5. The intensity and duration of the first storm event are relatively higher and shorter compared to the second storm event.

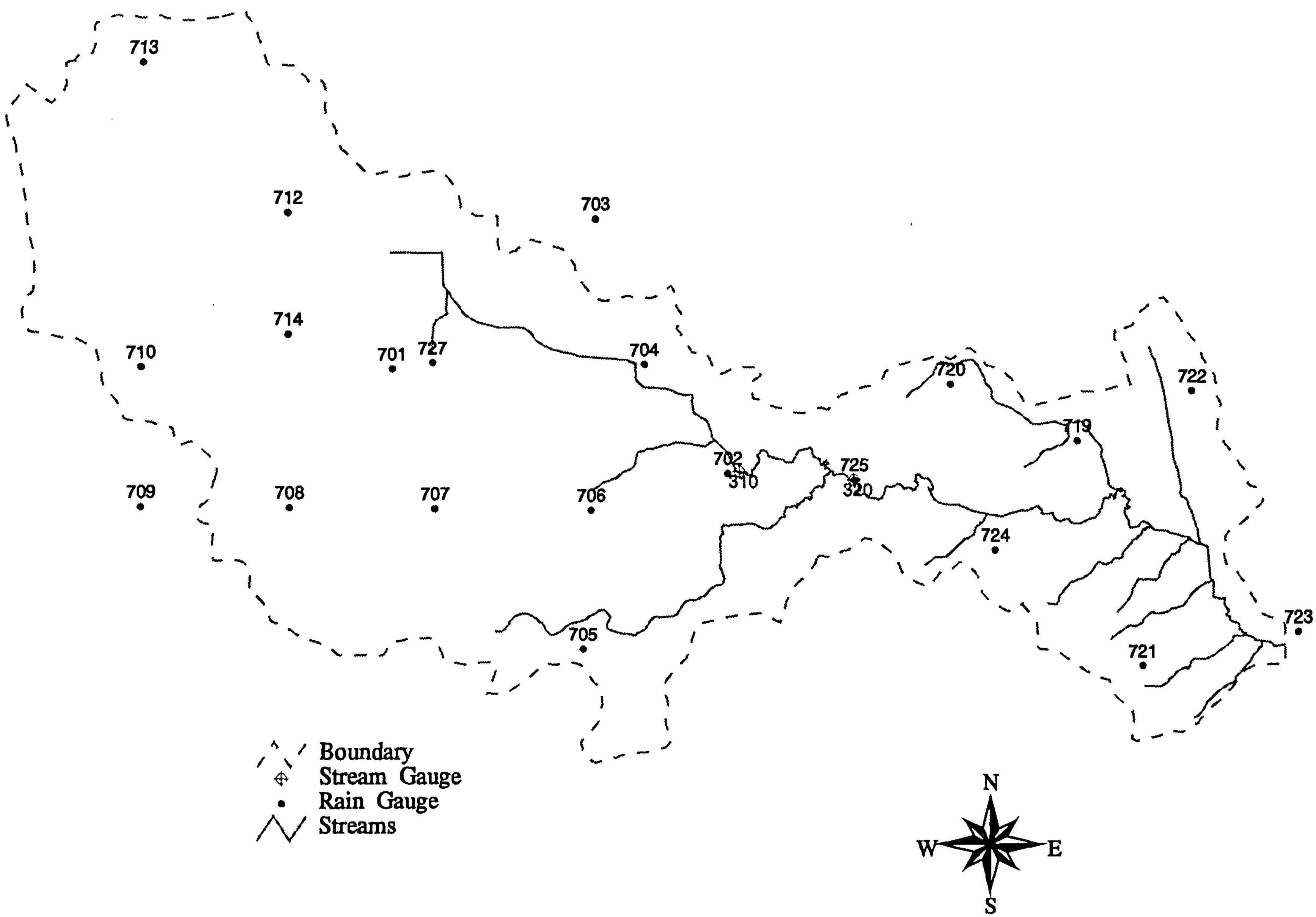


Figure 3.17 Location of rainfall and stream gauge stations in the Walnut Creek watershed

Table 3.4 Rainfall data for storm event on Julian day 197, 1992

| Time | Rainfall (m) at stations | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (min) | st703 | st704 | st705 | st706 | st707 | st708 | st709 | st710 | st712 | st713 | st714 | st719 | st720 | st721 | st722 |
| 1150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1155 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000762 | 0 |
| 1160 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000762 | 0.000508 | 0.001016 | 0.000508 |
| 1165 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1170 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1175 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1180 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1185 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1190 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 |
| 1195 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0.004826 | 0.00508 | 0.005588 | 0.01067 | 0.004064 | 0 | 0 | 0 | 0 |
| 1200 | 0.01092 | 0.00787 | 0.004064 | 0.005842 | 0.01067 | 0.00838 | 0.0094 | 0.01168 | 0.0127 | 0.01016 | 0.01422 | 0 | 0.00127 | 0 | 0 |
| 1205 | 0.00864 | 0.01372 | 0.0127 | 0.01245 | 0.01778 | 0.00991 | 0.01194 | 0.01168 | 0.00889 | 0.00864 | 0.01194 | 0.00381 | 0.00787 | 0.003556 | 0.002032 |
| 1210 | 0.00711 | 0.00889 | 0.01194 | 0.00864 | 0.01016 | 0.00737 | 0.005842 | 0.00635 | 0.006096 | 0.005588 | 0.006096 | 0.00737 | 0.00864 | 0.01346 | 0.00914 |
| 1215 | 0.00381 | 0.00381 | 0.004318 | 0.00381 | 0.00381 | 0.004064 | 0.004318 | 0.004318 | 0.003302 | 0.00381 | 0.003302 | 0.005334 | 0.00508 | 0.006096 | 0.004318 |
| 1220 | 0.002286 | 0.002032 | 0.003556 | 0.00254 | 0.003302 | 0.002794 | 0.002794 | 0.002032 | 0.00254 | 0.00254 | 0.00254 | 0.00254 | 0.002032 | 0.002286 | 0.003556 |
| 1225 | 0.00127 | 0.001524 | 0.00254 | 0.001524 | 0.002032 | 0.002032 | 0.001524 | 0.001524 | 0.00127 | 0.00127 | 0.001778 | 0.001016 | 0.001016 | 0.00127 | 0.002286 |
| 1230 | 0.00127 | 0.001016 | 0.00127 | 0.001016 | 0.001016 | 0.000762 | 0.000508 | 0.000762 | 0.00127 | 0.00127 | 0.000762 | 0.000762 | 0.000762 | 0.001016 | 0.000762 |
| 1235 | 0.000762 | 0.000762 | 0.000508 | 0.000762 | 0.000762 | 0.000508 | 0.000254 | 0.000254 | 0.000762 | 0.000508 | 0.000508 | 0.000762 | 0.001016 | 0.00127 | 0.000762 |
| 1240 | 0.000508 | 0.000508 | 0.000508 | 0.000254 | 0.000254 | 0.000508 | 0.000762 | 0.000254 | 0.000254 | 0 | 0.000254 | 0.000508 | 0.000508 | 0.001016 | 0.000762 |
| 1245 | 0.000254 | 0 | 0.000762 | 0.000508 | 0.000508 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0.000508 | 0 |
| 1250 | 0 | 0.000254 | 0.000508 | 0.000254 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000508 | 0 |
| 1255 | 0 | 0 | 0.000762 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0.000508 | 0 |
| 1260 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000762 | 0.000254 |
| 1265 | 0 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0.000254 | 0 |
| 1270 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1275 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1280 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1285 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1290 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1295 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1305 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 3.5 Rainfall data for storm event on Julian day 220, 1992

| Time | Rainfall (m) at stations | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (min) | st703 | st704 | st705 | st706 | st707 | st708 | st709 | st710 | st712 | st713 | st714 | st719 | st720 | st721 | st722 |
| 330 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 335 | 0 | 0 | 0 | 0 | 0.000254 | 0.000254 | 0.000508 | 0.000508 | 0 | 0.000254 | 0.000254 | 0 | 0 | 0 | 0 |
| 340 | 0.000254 | 0.000254 | 0.000508 | 0.000254 | 0.000254 | 0.001016 | 0.00127 | 0.000508 | 0.000508 | 0.000508 | 0.000508 | 0 | 0.000254 | 0 | 0.000254 |
| 345 | 0.000762 | 0.00127 | 0.00254 | 0.00254 | 0.003302 | 0.00381 | 0.003048 | 0.003048 | 0.002286 | 0.000762 | 0.005334 | 0.000762 | 0.000254 | 0.000762 | 0.000508 |
| 350 | 0.00254 | 0.001778 | 0.001524 | 0.00127 | 0.001524 | 0.001016 | 0.001016 | 0.00127 | 0.002794 | 0.003556 | 0.001524 | 0.002794 | 0.003302 | 0.001524 | 0.001016 |
| 355 | 0.001524 | 0.001524 | 0.000508 | 0.001016 | 0.001524 | 0.001016 | 0.001016 | 0.000762 | 0.000762 | 0.001016 | 0.000762 | 0.00127 | 0.001778 | 0.001524 | 0.00127 |
| 360 | 0.000762 | 0.000508 | 0.000508 | 0.000508 | 0.000762 | 0.000762 | 0.000762 | 0.000762 | 0.000762 | 0.000762 | 0.000762 | 0.001016 | 0.001016 | 0.001524 | 0.00127 |
| 365 | 0.001016 | 0.001016 | 0.000762 | 0.001016 | 0.00127 | 0.001016 | 0.000762 | 0.001016 | 0.001016 | 0.001016 | 0.000762 | 0.000508 | 0.000508 | 0.000762 | 0.000762 |
| 370 | 0.000762 | 0.001016 | 0.000762 | 0.000762 | 0.000762 | 0.000762 | 0.000762 | 0.000508 | 0.000508 | 0.000508 | 0.000762 | 0.000508 | 0.000762 | 0.000762 | 0.000508 |
| 375 | 0.000762 | 0.000762 | 0.000762 | 0.001016 | 0.00127 | 0.001016 | 0.000762 | 0.000762 | 0.000762 | 0.000508 | 0.000762 | 0.001016 | 0.001016 | 0.000762 | 0.000762 |
| 380 | 0.001016 | 0.001016 | 0.000508 | 0.000762 | 0.000508 | 0.000254 | 0.000254 | 0.000254 | 0.000508 | 0.000508 | 0.000254 | 0.000762 | 0.001016 | 0.001016 | 0.001016 |
| 385 | 0.000508 | 0.000508 | 0.000762 | 0.000762 | 0.000254 | 0.000508 | 0.000254 | 0.000254 | 0.000254 | 0.000254 | 0.000254 | 0.001016 | 0.000762 | 0.000762 | 0.000762 |
| 390 | 0.000254 | 0.000508 | 0.000508 | 0.000508 | 0.000254 | 0.000254 | 0.000254 | 0.000254 | 0.000254 | 0.000254 | 0.000254 | 0.000508 | 0.000508 | 0.001016 | 0.000762 |
| 395 | 0.000508 | 0.000508 | 0.000254 | 0.000254 | 0.000508 | 0.000254 | 0.000254 | 0.000508 | 0.000508 | 0.000254 | 0.000508 | 0.000508 | 0.000762 | 0.000508 | 0.000508 |
| 400 | 0.000254 | 0.000508 | 0.001016 | 0.000762 | 0.00127 | 0.001016 | 0.002794 | 0.00127 | 0.000508 | 0.000508 | 0.000762 | 0.000508 | 0.000508 | 0.000508 | 0.000508 |
| 405 | 0.001778 | 0.003302 | 0.00381 | 0.004572 | 0.004318 | 0.003048 | 0.002032 | 0.002794 | 0.00254 | 0.001016 | 0.00254 | 0.000762 | 0.000762 | 0.000508 | 0.000508 |
| 410 | 0.003048 | 0.002794 | 0.000254 | 0.000508 | 0.000254 | 0 | 0 | 0.000762 | 0.00127 | 0.002032 | 0.000508 | 0.001524 | 0.004826 | 0 | 0.000762 |
| 415 | 0.000254 | 0 | 0.000254 | 0 | 0 | 0.000254 | 0 | 0 | 0.000254 | 0 | 0.000254 | 0.000508 | 0.000508 | 0.000254 | 0.000762 |
| 420 | 0 | 0 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0.000254 | 0 | 0.000254 | 0 |
| 425 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 430 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 435 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 440 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 |
| 445 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 450 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 455 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0 |
| 460 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 465 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 |
| 470 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000762 | 0 | 0 | 0 | 0 | 0 |
| 475 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002032 | 0 | 0 | 0 | 0 | 0 |
| 480 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 485 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 |
| 490 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 495 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 505 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 3.5 (continued)

| Time | Rainfall (m) at stations | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (min) | st703 | st704 | st705 | st706 | st707 | st708 | st709 | st710 | st712 | st713 | st714 | st719 | st720 | st721 | st722 |
| 510 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 515 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 520 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0.000254 | 0.00127 | 0 | 0 | 0 | 0 | 0 |
| 525 | 0.000254 | 0 | 0 | 0 | 0.000254 | 0.000254 | 0.000254 | 0.000762 | 0.001016 | 0.00127 | 0.000762 | 0 | 0 | 0 | 0 |
| 530 | 0.000508 | 0.000254 | 0 | 0 | 0 | 0 | 0.000508 | 0.000762 | 0.001778 | 0.002032 | 0.000762 | 0 | 0 | 0 | 0 |
| 535 | 0.000508 | 0 | 0 | 0 | 0.000254 | 0.000254 | 0.000254 | 0.001524 | 0.003048 | 0.002794 | 0.00127 | 0 | 0 | 0 | 0 |
| 540 | 0.000762 | 0.000254 | 0 | 0 | 0 | 0 | 0.000254 | 0.002032 | 0.003302 | 0.004064 | 0.000762 | 0 | 0 | 0 | 0 |
| 545 | 0.000508 | 0 | 0 | 0 | 0 | 0.000254 | 0.002794 | 0.006858 | 0.00737 | 0.00635 | 0.00508 | 0 | 0 | 0 | 0 |
| 550 | 0.005334 | 0.00127 | 0.000254 | 0.000254 | 0.003048 | 0.005588 | 0.006604 | 0.00381 | 0.003556 | 0.002032 | 0.005334 | 0 | 0 | 0 | 0 |
| 555 | 0.003048 | 0.01041 | 0.002032 | 0.006858 | 0.01143 | 0.00737 | 0.003556 | 0.00127 | 0.001778 | 0.000508 | 0.001524 | 0 | 0.000762 | 0 | 0 |
| 560 | 0.00127 | 0.006096 | 0.006858 | 0.00737 | 0.00381 | 0.00127 | 0.000508 | 0.000508 | 0.001016 | 0.000508 | 0.001016 | 0.003048 | 0.00914 | 0 | 0.002794 |
| 565 | 0.000508 | 0.001016 | 0.001016 | 0.000254 | 0 | 0.000254 | 0.000254 | 0.000254 | 0 | 0 | 0 | 0.00991 | 0.005588 | 0.002794 | 0.01041 |
| 570 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000762 | 0.000254 | 0.004318 | 0.001016 |
| 575 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 | 0.000254 |
| 580 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 | 0 | 0 |
| 585 | 0 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 590 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 595 | 0.000254 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 | 0 | 0 |
| 600 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 605 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 610 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 615 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 620 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 625 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 630 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 635 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 640 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000254 |
| 645 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 650 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 655 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 660 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 665 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 670 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*3.4.3 Result of Example Application*

The simulation results of the first event at the stream gauge station 310 and 320 are shown in Figures 3.18 and 3.19, respectively. As can be seen in these figures, the simulation model predicted a rapid accumulation of flow and gradual recession of the hydrographs at both monitoring stations. Since station 320 is situated downstream of station 310, the flow rate is relatively higher than the flow rate at station 310. The simulation results of the second storm event (Julian day 220 in 1992) at stream gauge station 310 and 320 are also summarized in Figure 3.20 to Figure 3.21. The magnitude of the flow rate in the second storm event is relatively lower and smoother than for the first storm event that occurred on Julian day 197 in 1992. Overall, the model seems to be efficient in its prediction of stream flow hydrograph, given the assumptions made during its development.

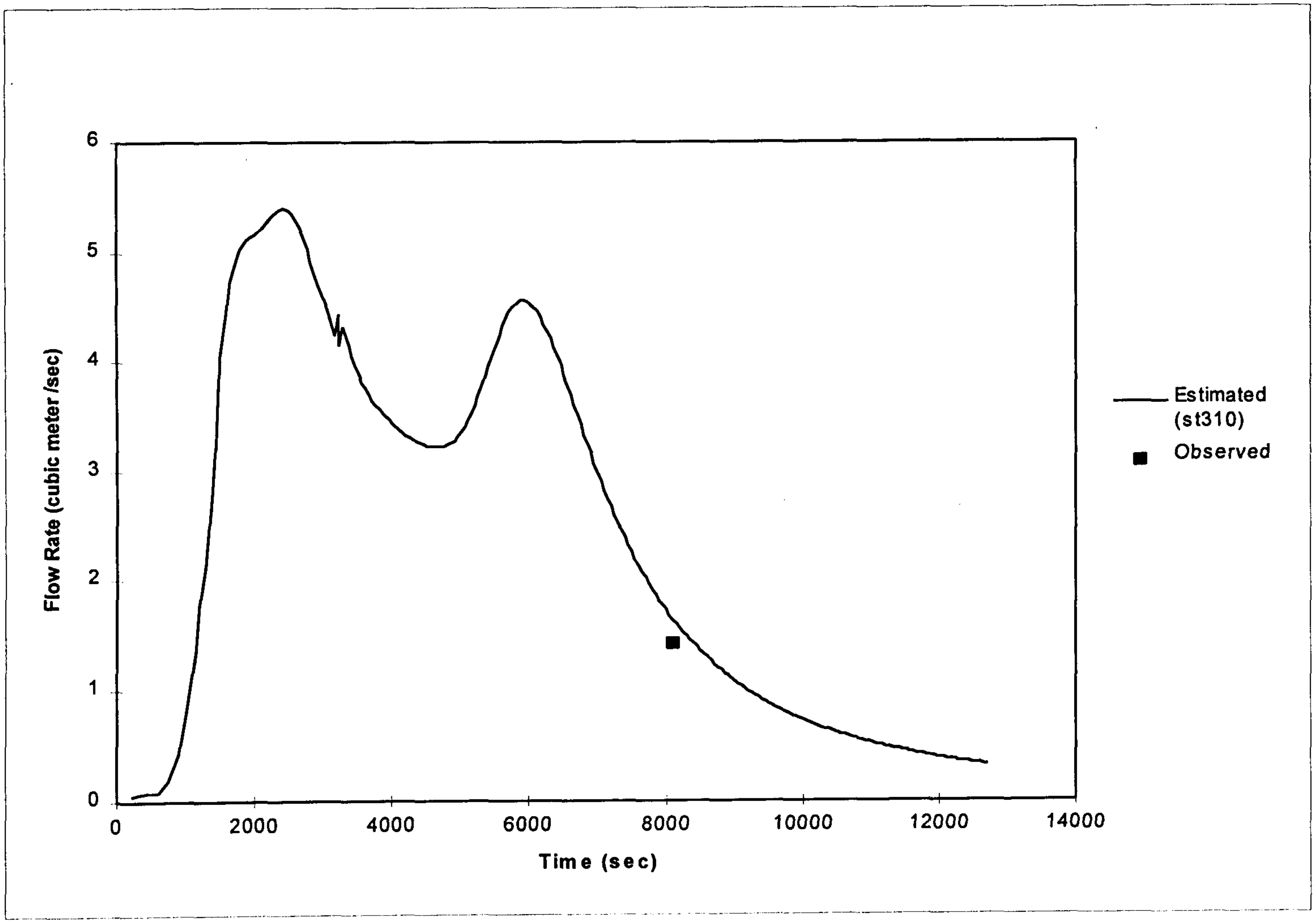


Figure 3.18 Simulated streamflow hydrograph at station 310 for storm event on Julian day 197, 1992.

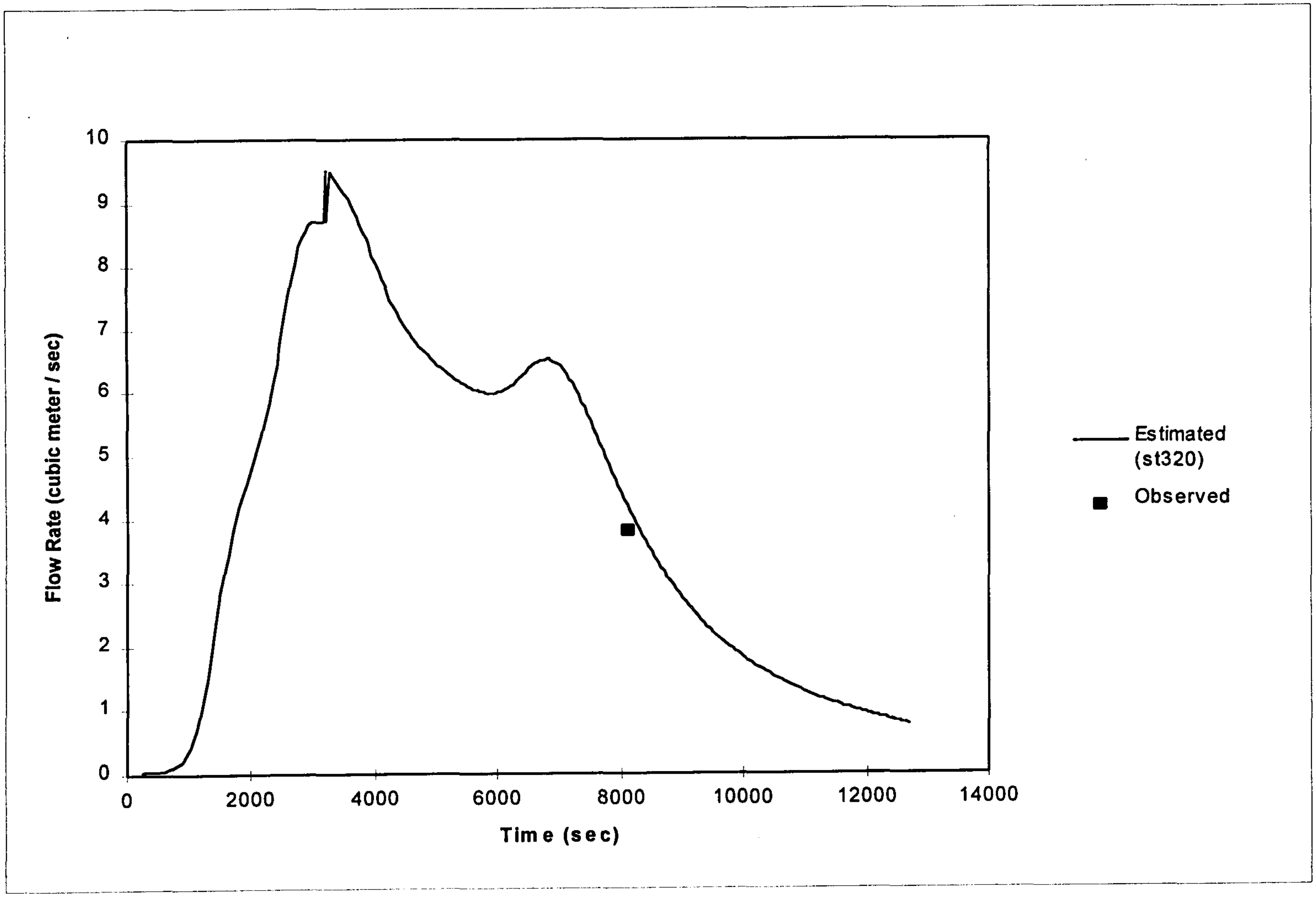


Figure 3.19 Simulated streamflow hydrograph at station 320 for storm event on Julian day 197, 1992.

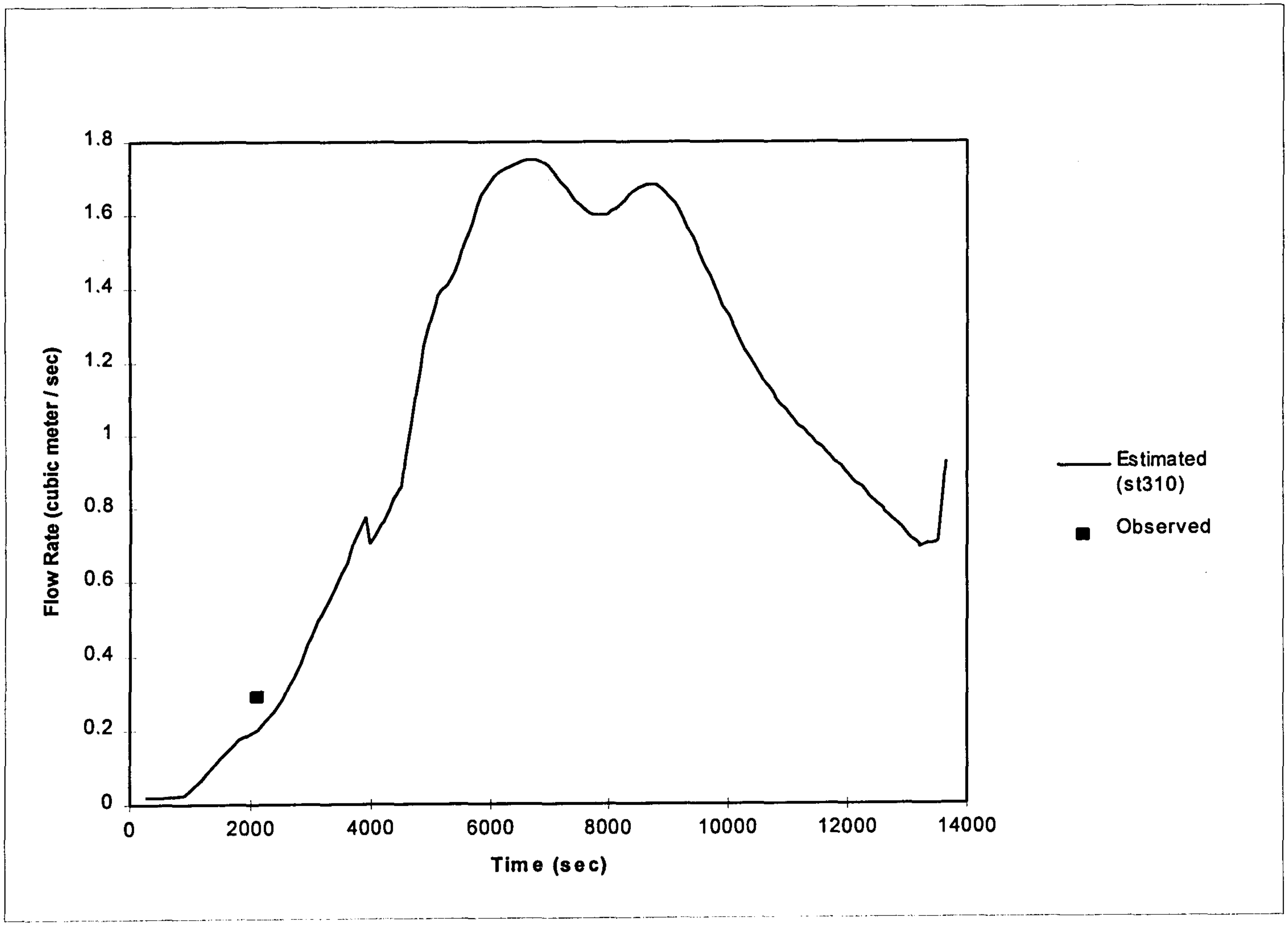


Figure 3.20 Simulated streamflow hydrograph at station 310 for storm event on Julian day 220, 1992.

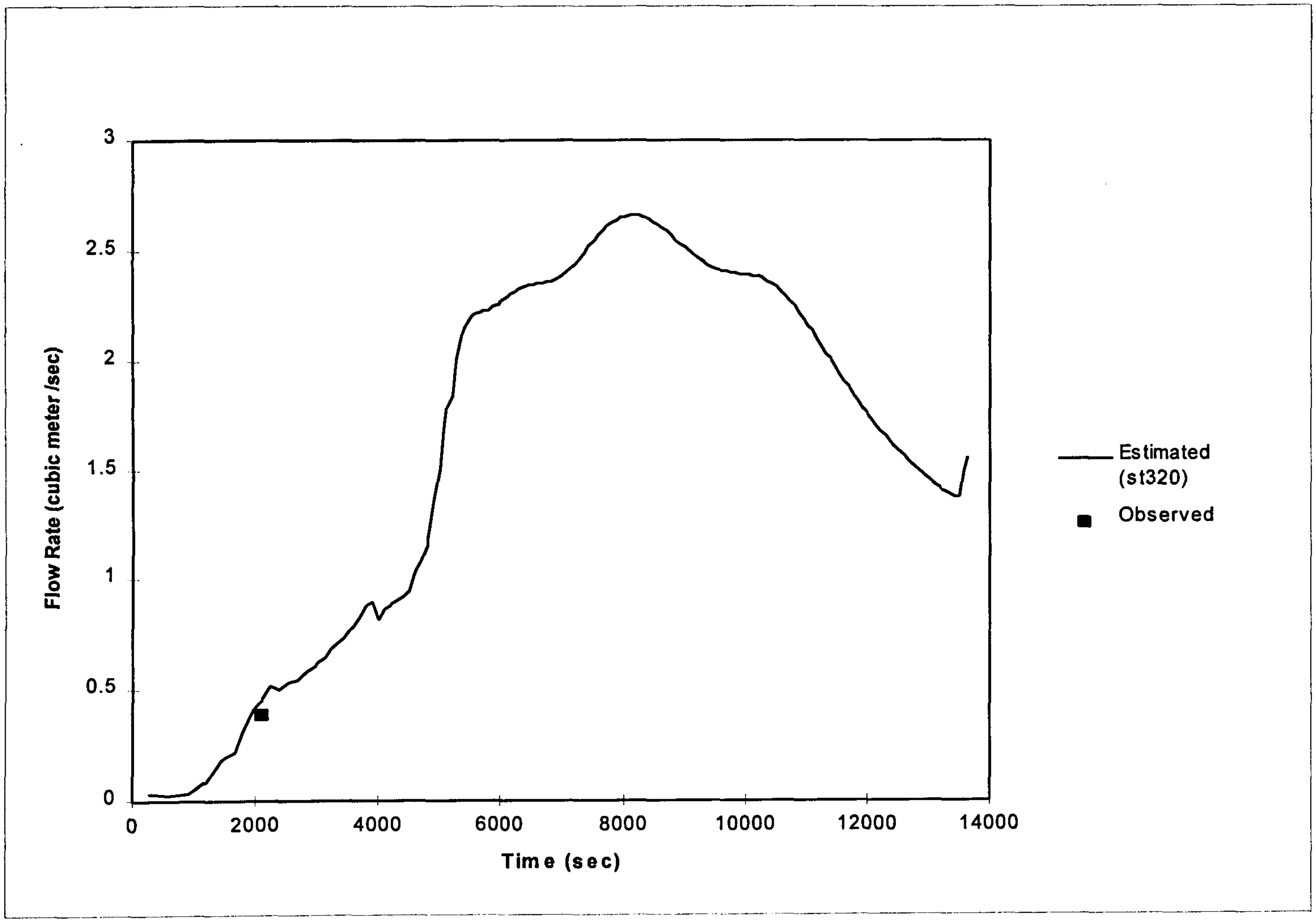


Figure 3.21 Simulated streamflow hydrograph at station 320 for storm event on Julian day 220, 1992.

# 4. SUMMARY AND CONCLUSIONS

In this study, a physically-based and process-oriented surface hydrologic model was developed using the functionality of GIS. As opposed to traditional spatial modeling techniques, the surface hydrologic model developed in this study utilizes full integration of the equation modules with GIS. There is a need to develop models that are both physically based, process-oriented and at the same time are easier to use and utilize the spatial data management functions of the GIS. In the study, the generic functions and operations residing in the GIS facilitate organization and preparation of spatially variable input parameters for modeling. In distributed modeling, the capability to display and visualize large volumes of input and output data by the GIS makes modeling cost-effective and also enables the interpretation of results. Furthermore, the use of graphical user interface enhances user navigation of the entire modeling system, eliminating, in most cases, cumbersome data entry tasks and the learning of complicated program commands.

The modeling system was applied to simulate watershed hydrology. A predominantly agricultural watershed - the Walnut Creek watershed - was chosen for this example application. The performance of the modeling system is restricted to the lack of groundwater component and tile drainage system. The result hydrograph presented a higher peak hydrograph and shorter recession limb than the observed values in the heavy short storm event. These may be due to the influence of the groundwater component can be considered in rising part of the hydrograph and recession part. In the beginning of the storm event, because groundwater table is lower than the channel surface, the water flow in channel should discharge to the groundwater and flow rate in channel is reduced. In the recession period, the groundwater table is higher than the channel surface and groundwater should recharge into channel and increase the flow rate in the channel. Likewise, the tile flow will decrease the channel flow rate in the rising limb and increase the channel flow rate in the recession limb.

# 5. RECOMMENDATIONS FOR FURTHER RESEARCH

Further research to improve the simulation result of WSHMS is necessary in the following areas: incorporating the groundwater component into WSHMS; adding the tile drainage system into WSHMS; refining evapotranspiration component; improving the accuracy of the data.

The channel flow may first discharge to the groundwater flow in the beginning of the storm event and recharge from groundwater flow after the groundwater table raises higher than the channel flow surface. The tile drainage system is also a component of the groundwater routing system in the agricultural watershed that will influence the flow rate of the groundwater and recharge of the channel flow.

The evapotranspiration component in WSHMS using the constant daily rate for the storm event will need refine to be a standing along module or component of data preprocessing module to provide evapotranspiration distribution during the storm event. The surface runoff simulation that depends on land use and land cover; thus the simulation results can be significantly improved by using more accurate land cover information, satellite remote sensing.

# APPENDIX: WSHMS ARC MARCO LANGUAGE PROGRAM

## A.1 WSHMS Main Function

**wshms.aml**

```
/*****************************************************************
/* Watershed Surface Hydrologic Modeling System
/* Program: wshms.AML
/* Function: The main aml file of WSHMS
/*         Start the user-friendly environment and interface
/* Chi-Chuan Chen 09-11-95 1st ed
/* Chi-Chuan Chen Jan.1996 2nd ed
/*****************************************************************

&terminal 9999
&sv amlws [show &workspace]
&amlpath  [show &amlpath],%amlws%/saint, %amlws%, %amlws%/preproc
&menupath  [show &menupath],%amlws%/saint, %amlws%, %amlws%/preproc

&menu ws.menu &STRIPE 'WSHMS - Workspace'

&thread &create WSHMS &menu wshms.menu &STRIPE ~
  'Watershed Surface Hydrologic Modeling System' &pos &ul &screen &ul
&sv .wshmsr [after [show &thread &size wshms] , ]
&sv .wshmsc [before [show &thread &size wshms] , ]
&sv .wshmsr %.wshmsr% + 20

display  9999  size %.wshmsc% [truncate [calc %.wshmsc% * 0.65 ] ] position 0 0 ~
screen 0 %.wshmsr%
&thread &delete &self
&return
```

**ws.menu**

```
7 ws.menu
  Enter the Preferred Workspace   %input1
  %b1
%input1 INPUT .covws 20 TYPEIN yes SCROLL NO REQUIRED  character
%b1 BUTTON KEEP 'APPLY'  ws %.covws%; &return
```

**wshms.menu**

```
1 wshms.menu
'System PreProcessing'
  'Convert contour to DEM'   &thread &create con2dem &menu~
     con2dem.menu &stripe 'DEM Generation' &pos &right &display
  'Calculate  x and y slopes'  &thread &create con2dem &menu~
     2dslope.menu &stripe 'Slope Calculation' &pos &right &display
  'Compute cell roughness coefficient' &thread &create roughcoe &menu ~
     rough.menu &stripe 'Roughness Computation' &pos &right &display
  'Set up channel system'  &thread &create channel &menu~
```

```
    channel.menu &stripe 'Channel System' &pos &right &display
  'Compute Infiltration Parameters' &thread &create infil &menu~
    infiltration.menu &stripe 'Infiltration Parameters' &pos &right~
    &display
  'Generate Rainfall Data' &thread &create rain &menu raininfo.menu~
    &stripe 'Rainfall Data Generation'  &pos &right &display
'Initial Condition' &thread &create initcond &menu init.menu &stripe ~
      'Initial Conditions Set Up' &pos &right &display
'Event Processing' &sv .optype = 3; &thread &create newevent &menu ~
   newsaint1.menu &stripe 'Overland/Channel Flow Modeling Module' ~
   &pos &right &display
'Retrieve Information' &sv .optype = 4; &thread &create oldevent &menu ~
   saintold.menu &stripe 'Overland/Channel Flow Modeling Module Using Existing Data' ~
   &pos &right &display
Quit &return
```

## A.2 Data Preprocessing

**con2dem.menu**

```
7 con2dem.menu
 Convert Contour Coverage to DEM

  Enter the Contour           Enter the Watershed
  Coverage                    Boundary Coverage
  %input1                     %input2




  Enter the cellsize of the grid (m)  %input3
  Enter the output DEM grid name    %input4
  %button1         %button2
%formopt messagevariable .messdem
%input1 INPUT .concover 18 TYPEIN no SCROLL yes ROWS 3 required Cover ~
  -SORT
%input2 INPUT .bndcover 18 TYPEIN no SCROLL yes ROWS 3 required Cover ~
  -SORT
%input3 INPUT .cellsize 11 TYPEIN YES SCROLL NO ~
 INITIAL '100'  INTEGER
%input4 INPUT .elev  11 TYPEIN yes SCROLL NO character
%button1 BUTTON KEEP 'APPLY'  &r con2dem.aml ; &RETURN
%button2 BUTTON KEEP 'EXIT' &RETURN
```

**con2dem.aml**

```
/*************************************************************
/* Watershed Delineation Management  System
/* PROGRAM: con2dem.aml
/* FUNCTION: convert contour Coverage to Tin then Lattice.
/*************************************************************
&if [exists temptin1 -tin] &then  &do   kill temptin1 all   &end
&if [exists tempgrid1 -grid] &then  &do   kill tempgrid1 all   &end
&if [exists %.elev% -grid] &then  &do  kill %.elev% all   &end

/* CreateTin from a contour.
createtin temptin1
cover %.concover% line elev
end

&describe %.bndcover%
&sv .xmin = %DSC$XMIN% - %.cellsize% / 2
&sv .ymin = %DSC$yMIN% - %.cellsize% / 2
&sv .xmax = %DSC$XMAX% + %.cellsize% / 2
&sv .ymax = %DSC$YMAX% + %.cellsize% / 2
&sv .pgxmin =  %DSC$XMIN%
&sv .pgymin =  %DSC$YMIN%
```

```
/* Convert tin to a lattice(float grid).
tinlattice temptin1 tempgrid1
%.xmin%, %.ymin%
%.xmax%, %.ymax%
~
%.cellsize%

/* Clip lattice with watershed boundary coverage.
polygrid %.bndcover% tempbnd1
%.cellsize%
N
%.pgxmin%, %.pgymin%
82, 139
NODATA

&DATA ARC grid
%.elev% = con(tempbnd1, tempgrid1)
quit
&END

&return
```

**2d_slope.menu**

```
/*  2 Dimensional Slope Calculation  */
7 2dslope.menu
  Select DEM
  %input1




  Enter the output xslope grid name  %input3
  Enter the output yslope grid name  %input4
  %button1          %button2
%input1 INPUT .elev 18 TYPEIN no SCROLL yes ROWS 3 required GRID ~
  -SORT
%input3 INPUT .sx 11 TYPEIN YES SCROLL NO character
%input4 INPUT .sy 11 TYPEIN yes SCROLL NO character
%button1 BUTTON KEEP 'APPLY'  &r 2d_slope1.aml ; &RETURN
%button2 BUTTON KEEP 'EXIT' &RETURN
```

**2d_slope.aml**

```
/*******************************************************
/* Program: 2d_slope.aml
/* Function: Slope Calculation
/* %.elev% elevation grid.
/* %.sx% x direction geometry slope grid.
/* %.sy% y direction geometry slope grid.
/* *****************************************************
&if [exists %.sx% -grid ] &then   &do   kill %.sx% all   &end
```

```
&if [exists %.sy% -grid] &then   &do   kill %.sy% all   &end
&if [exists %.qx% -grid] &then   &do   kill %.qx% all   &end
&if [exists %.qy% -grid] &then   &do   kill %.qy% all   &end
&if [exists %.roughness% -grid] &then   &do   kill %.roughness% all   &end

&if [show PROGRAM] ne 'GRID' &then
 &do
    &if [show PROGRAM] = 'ARC' &then
       &do   GRID   &end
    &else
       &do   quit;   GRID   &end
 &end

/* head, x flow rate, y flow rate - intial grids = 0
/* convert the roughness to grid
 %.hprevious% = 0 * %.elev%
 %.qx% = 0 * %.elev%
 %.qy% = 0 * %.elev%
 %.roughness% = %.rough% * ( 1 + 0 * %.elev% )

docell
 %.sx% = ( %.elev%(-1,0) - %.elev% )/ %.width%
 %.sy% = ( %.elev%(0,-1) - %.elev% )/ %.width%
end
```

**rough.menu**

```
/* Converting the land use coverage to grid */
7 rough.menu
  Enter the land          Enter the existing
  use coverage            DEM grid
  %input1                 %input2



  Enter the output grid name   %input3
  %button1         %button2
%input1 INPUT .landusec 18 TYPEIN no SCROLL yes ROWS 3 required Cover -SORT
%input2 INPUT .elev 18 TYPEIN no SCROLL yes ROWS 3 required Grid -SORT
%input3 INPUT .landuseg 18 TYPEIN yes SCROLL NO character
%button1 BUTTON KEEP 'APPLY'  &sv .vitem [GETITEM %.landusec% -POLYGON ~
];&r rough.aml ; &RETURN
%button2 BUTTON KEEP 'EXIT' &RETURN
```

**rough.aml**

```
&describe %.elev%
&sv .pgxmin = %GRD$XMIN%
&sv .pgymin = %GRD$YMIN%
&sv .nocols = %GRD$NCOLS%
&sv .norows = %GRD$NROWS%
&sv .cellsize = %GRD$DX%
```

```
/* Convert the land use coverage to grid using the specified item value
polygrid %.landusec% %.landuseg% %.vitem%
%.cellsize%
N
%.pgxmin%, %.pgymin%
%.norows%, %.nocols%
NODATA
```

**channel.menu**

```
/*      Produce Grid River System from Line Coverage */
7 channel.menu
   Enter the stream        Select Existing
   Coverage               DEM Grid
   %input1                %input2




Enter the stream system grid   %input5
  %button1          %button2
%input1 INPUT .riverc 18 TYPEIN no SCROLL yes ROWS 3 required Cover -SORT
%input2 INPUT .elev 18 TYPEIN no SCROLL yes ROWS 3 required Grid -SORT
%input5 INPUT .riverg  11 TYPEIN yes SCROLL NO  character
%button1 BUTTON KEEP 'APPLY'  &sv .orderitem [getitem %.riverc% -ARC~
 'Stream Order Item']; &r riverc2g.aml; &return
%button2 BUTTON KEEP 'EXIT' &return
```

**riverc2g.aml**

```
/************************************************************************
/* PROGRAM: riverc2g.aml
/* FUNCTION: Convert river coverage to grid by stream order
/* Call by channel.menu
/* Chi-Chuan Chen January 1996 1st ed
/************************************************************************
/* Eliminating the existing destination Grid and intermediate dummy grid
&if [exists %.riverg% -GRID] &then kill  %.riverg% all
&if [exists tempr1  -GRID] &then kill  tempr1 all
&if [exists tempr2  -GRID] &then kill  tempr2 all
&if [exists tempr3  -GRID] &then kill  tempr3 all
&if [exists tempr4  -GRID] &then kill  tempr4 all

&describe %.elev%
&sv .cellsize = %GRD$DX%
&sv .xmin = %GRD$XMIN%
&sv .ymin = %GRD$YMIN%
&sv .ncols = %GRD$NCOLS%
&sv .nrows = %GRD$NROWS%
&sv .zmax = %GRD$ZMAX%
```

```
&DATA ARC
 linegrid %.riverc% tempr1 %.orderitem%
 %.cellsize%
 N
 %.xmin% %.ymin%
 %.nrows% %.ncols%
 ~
 ~
 quit
&END
tempr2 = con(tempr1, %.elev%)
&describe tempr2
&sv .zmin = %GRD$ZMIN%
tempr3 = con(isnull(tempr1) & %.elev% , 500, tempr2  == %.zmin%, 500 - 15 * tempr1, ~
        500 - 10 * tempr1)
tempr4 = con(tempr1 , flowdirection(tempr3))
%.riverg% = con(tempr4 == 1,  1,tempr4 == 2,  2, tempr4 == 4,  3, tempr4 == 8,  4, ~
               tempr4 == 16,  5, tempr4 == 32,  6, tempr4 == 64,  7, tempr4 == 128, 8 )
gridshade %.riverg%
linecolor blue; arcs rivers
&return
```

**infiltration.menu**

```
/* Computing the Parameters of the Green-Ampt Equation */
7 infiltration.menu
  Enter the Soil          Enter the existing
  Coverage                DEM grid
  %input1                 %input2



  Hydraulic Conductivity output Grid  %input4
  Capillary Pressure Head output Grid  %input5
  %button1        %button2
%input1 INPUT .soil 18 TYPEIN no SCROLL yes ROWS 3 required Cover ~
 -SORT
%input2 INPUT .elev 18 TYPEIN no SCROLL yes ROWS 3 required Grid ~
  -SORT
%input4 INPUT .greenk  11 TYPEIN yes SCROLL NO ~
 character
%input5 INPUT .greencap  11 TYPEIN yes SCROLL NO ~
 character
%button1 BUTTON KEEP 'APPLY' &thread &create soilitem &modal &menu~
 soilitem.menu &stripe 'Soil items for Infiltration' &pos &below &thread infil
%button2 BUTTON KEEP 'EXIT' &RETURN
%formopt setvariables immediate
```

**infiltration.aml**

```
/*********************************************************************
/* PROGRAM: infiltration.aml
```

```
/* FUNCTION: compute the parameters of the Green-Ampt Equation.
/* Call by  infiltration.menu
/* Chi-Chuan Chen January 1996
/*************************************************************************

&describe %.elev%
&sv .pgxmin =  %GRD$XMIN%
&sv .pgymin =  %GRD$YMIN%
&sv .nocols =  %GRD$NCOLS%
&sv .norows =  %GRD$NROWS%
&sv .cellsize = %GRD$DX%

/* Convert the soil coverage to hydraulic conductivity grid using the specified conductivity item.
polygrid %.soil% %.greenk% %.itemk%
%.cellsize%
N
%.pgxmin%, %.pgymin%
%.norows%, %.nocols%
NODATA

/* Convert the land use coverage to grid using the specified capillar item.
polygrid %.soil% %.greencap%  %.itemcap%
%.cellsize%
N
%.pgxmin%, %.pgymin%
%.nocols%, %.norows%
NODATA
&return
```

**raininfo.menu**

```
/*      WSHMS PreProcessing System -- RainInfo */
7 raininfo.menu
  Enter the rainfall comma delimited text file
   (give the station name in the first line)  %input1
  Unit of the rainfall data   %choice1
  Output rainfall info table  %input2
  %button1          %button2
%input1 INPUT .txtfile 20 TYPEIN YES SCROLL NO REQUIRED file
%choice1 CHOICE .rainunit PAIRS INITIAL '1' ~
  'm' '1' 'cm' '0.01' 'mm' '0.001' 'feet' '0.3048' 'inch' '0.0254'
%input2 INPUT .raininfo 11 TYPEIN YES SCROLL NO CHARACTER
%button1 BUTTON KEEP 'APPLY' &r raininfo.aml; &RETURN
%button2 BUTTON KEEP 'EXIT' &RETURN
```

**raininfo.aml**

```
/***************************************************
/* PROGRAM: raininfo.aml
/* called by raininfo.menu
/* FUNCTION: import rainfall data into info table
/***************************************************
```

```
&sv closestatus [close -all]
 /* test file and constant
 /* &sv .rainunit 0.001
 /* &sv .textfile /home/taiwan/nstl/nstl/demo.csv
 /* &sv .raininfo test.dat
quit
tables
  &sv textfileu = [open %.textfile% ins -read]
  &sv tempfileu = [open tempfile wst -write]
  &sv stations = [read %textfileu% rst]
  &do &until %rst% <> 0
    &sv outst [write %tempfileu% [read %textfileu% rst] ]
  &end
  &sv closestatus [close -all]
&if [exists %.raininfo% -info] &then kill %.raininfo%
define %.raininfo%
test 4 4 c
~
sel
&sv ist = 1
&sv station%ist% [before %stations% ,]
additem %.raininfo% [value station%ist%] 8 8 i
&sv stations = [after %stations% ,]
&do &until [length %stations%] = 0
  &sv ist = %ist% + 1
  &sv station%ist% [before %stations% ,]
  additem %.raininfo% [value station%ist%] 8 12 f 10
  &sv stations = [after %stations% ,]
&end
dropitem %.raininfo% test
sel %.raininfo%
add from tempfile
&sv j = 2
&do &while %j% <= %ist%
   cal [value station%j%] = %.rainunit% * [value station%j%]
   &sv j = %j% + 1
&end
&type [delete tempfile -FILE]
quit
grid
&return
```

## A.3 Initial Conditions

**initial.menu**

```
/* Computing the Parameters of the Green-Ampt Equation */
7 infiltration.menu
  Enter the Soil         Enter the Watershed
  Coverage               Boundary Coverage
  %input1                %input2



  Hydraulic Conductivity output Grid  %input4
  Capillary Pressure Head output Grid  %input5
  %button1         %button2
%input1 INPUT .soil 18 TYPEIN no SCROLL yes ROWS 3 required Cover ~
  -SORT
%input2 INPUT .bndcover 18 TYPEIN no SCROLL yes ROWS 3 required Cover ~
  -SORT
%input4 INPUT .conductivity  11 TYPEIN yes SCROLL NO ~
  character
%input5 INPUT .capillary  11 TYPEIN yes SCROLL NO ~
  character
%button1 BUTTON KEEP 'APPLY'  &r infiltration.aml ; &RETURN
%button2 BUTTON KEEP 'EXIT' &RETURN
```

**init.aml**

```
/*****************************************************************
/* Program:init.aml
/* Function:
/* 1) use flow direction and inlet node grids, and initial
/*   flow rate at the nodes to generate the initial flow rate
/* 2) using secant method to interpolate and find solution
/*   of flow depth when given flow rate, roughness, slope,
/*   bank slope (z), and bottom width. (Manning Eq.)
/* Call by init.menu
/* Chi-Chuan Chen    Mar 31 1996
/*****************************************************************

/* Initial Flow Rate by Flow Accumulation  */

  &if [exists %.initq% -GRID] &then kill %.initq% all
  &if [exists temprq -GRID] &then kill temprq all
  temprq = flowaccumulation( %.dir128g% , ~
        con(%.rivnode% == 0, %.initinlet%, %.dir128g% * 0 ) )
  %.initq% = con( %.dir128g% & temprq == 0, %.initinlet%, temprq)
  kill temprq all

/* Trapezoid Channel with bank slope z = 1.5  */
&IF ( %.channeltype% = 1 ) &THEN
 &DO
  &sv .rslope  elevdif
```

```
&sv .zz     1.5
&sv z2p1    [SQRT [calc %.zz% * %.zz% + 1] ]

&if [exist %.initdepth% -GRID] &then kill %.initdepth% all
&if [exist %.initarea% -GRID] &then kill %.initarea% all

DOCELL
 d1 := 0
 d2 := 5
 sn := pow(%.rslope%,0.5) / %.rivrough%
 f1 := sn * pow( (%.bwidth% + %.zz% * d1) * d1, 1.6667)~
    / pow(%.bwidth% + 2 * d1 * %z2p1% , 0.6667) - %.initq%
 f2 := sn * pow( (%.bwidth% + %.zz% * d2) * d2, 1.6667)~
    / pow(%.bwidth% + 2 * d2 * %z2p1% , 0.6667) - %.initq%
 d3 := d1 - (d2 - d1) * f1 / (f2 - f1)
 f3 := sn * pow( (%.bwidth% + %.zz% * d3) * d3, 1.6667)~
    / pow(%.bwidth% + 2 * d3 * %z2p1% , 0.6667) - %.initq%
while ( abs(f3) > 0.00001)
 {
   if (f3 > 0)
     begin
       d2 := d3
       f2 := f3
     end
   else
     begin
       d1 := d3
       f1 := f3
     end
  endif
  d3 := d1 - (d2 - d1) * f1 / (f2 - f1)
  f3 := sn * pow( (%.bwidth% + %.zz% * d3) * d3, 1.6667)~
   / pow(%.bwidth% + 2 * d3 * %z2p1% , 0.6667) - %.initq%
 }
 %.initdepth% = d3
 END
 %.initarea% = (%.bwidth% + %.zz% * %.initdepth%) * %.initdepth%
&END
/* %.channeltype% = 2 -- rectangular channel */
&IF ( %.channeltype% = 2 ) &THEN
&DO
 &sv .rslope  elevdif
 &if [exist %.initdepth% -GRID] &then kill %.initdepth% all
 &if [exist %.initarea% -GRID] &then kill %.initarea% all

 DOCELL
  d1 := 0
  d2 := 5
  sn := pow(%.rslope%,0.5) / %.roughn%
  f1 := sn * pow( %.bwidth% * d1 , 1.6667)~
     / pow(%.bwidth% + 2 * d1 , 0.6667) - %.initq%
  f2 := sn * pow( %.bwidth% * d2 , 1.6667)~
```

```
    / pow(%.bwidth% + 2 * d2 , 0.6667) - %.initq%
  d3 := d1 - (d2 - d1) * f1 / (f2 - f1)
  f3 := sn * pow( %.bwidth% * d3 , 1.6667)~
    / pow(%.bwidth% + 2 * d3 , 0.6667) - %.initq%

 while ( abs(f3) > 0.00001)
 {
   if (f3 > 0)
     begin
       d2 := d3
       f2 := f3
     end
   else
     begin
       d1 := d3
       f1 := f3
     end
   endif
   d3 := d1 - (d2 - d1) * f1 / (f2 - f1)
   f3 := sn * pow( %.bwidth% * d3 , 1.6667)~
     / pow(%.bwidth% + 2 * d3 , 0.6667) - %.initq%
 }
 %.initdepth% = d3
END
%.initarea% = %.bwidth% * %.initdepth%
&END

/* Write the parameters to a file */
 &sv initunit [open %.initxt% status -WRITE]
   &sv outstatus [write %initunit% %.channeltype%]
   &sv outstatus [write %initunit% %.rivrough%]
   &sv outstatus [write %initunit% %.initinlet%]
   &sv outstatus [write %initunit% %.initq%]
   &sv outstatus [write %initunit% %.bwidth%]
   &sv outstatus [write %initunit% %.initarea%]
   &sv outstatus [write %initunit% %.initdepth%]
   &if ( %.channeltype% = 1 ) &then
     &do  &sv outstatus [write %initunit% %.zz%]  &end
  &sv outstatus [write %initunit% %.initinlet%]
 &sv ccc = [close %initunit%]

&return
```

## A.4 Simulation Function

**saintnew.menu**

```
/* 2D Saint Venant Equation for Overland Flow Calculation */
7 saintnew.menu
   Select Elevation          Select Rainfall
   Grid                   INFO file
   %input1                  %input2



   Select the RainGauge        Select the Stream
   Station Coverage           Direction Drid
   %input3                 %input4




  The Slope Grids: x: %input6      y: %input7
  Overland Flow Manning Roughness Grid   %input8
  The Initial Soil Moisture            %input13
  Time Interval for Output(min)          %input11
  Constant Slope for Overland to Stream  %input14
  Initial Condition Record File         %input9
  Output ASCII File Name               %input10
  Output Variable File Name            %input15
  Iterations for this run  %widget1
  %button1          %button2
%input1 INPUT .elev 18 TYPEIN no SCROLL yes ROWS 3 required GRID -SORT
%input2 INPUT .raindat 18 TYPEIN no SCROLL yes ROWS 3 required FILE e*.dat -INFO
%input3 INPUT .rainstcov 18 TYPEIN no SCROLL yes ROWS 3 required COVER -SORT
%input4 INPUT .dirg 18 TYPEIN no SCROLL yes ROWS 3 required GRID -SORT
%input6 INPUT .sx 11 TYPEIN yes SCROLL NO  INITIAL 'xslope' character
%input7 INPUT .sy 11 TYPEIN yes SCROLL NO  INITIAL 'yslope' character
%input8 INPUT .roughn 11 TYPEIN yes SCROLL NO  INITIAL 'rough' character
%input9 INPUT .initxt 11 TYPEIN yes SCROLL NO  INITIAL 'initxt' character
%input10 INPUT .outfile 11 TYPEIN yes SCROLL NO  character
%input11 INPUT .delta_t 11 TYPEIN yes SCROLL NO  INITIAL 60  integer
%input13 INPUT .initsm 11 TYPEIN yes SCROLL NO REAL
%input14 INPUT .bnks 11 TYPEIN yes SCROLL NO REAL
%input15 input .varfile 11 TYPEIN yes SCROLL NO  character
%widget1 SLIDER .runiters 30 step 5 init 15 integer 5 50
%button2 BUTTON KEEP 'EXIT' &RETURN
%button1 BUTTON KEEP 'APPLY' &sv .test_it = 1;~
       &r iter.aml; &RETURN
```

**saintold.menu**

```
/* 2D Saint Venant Equation for Overland Flow Calculation */
7 saintold.menu
  Enter the Variables File                %input1
  Enter Number of Iteration for Previous Simulation %input2
```

```
  Enter Number of Iteration for this run  %widget1
  %button1          %button2
%input1 INPUT .varfile 11 TYPEIN yes SCROLL NO REQUIRED  character
%input2 INPUT .stopiter 11 TYPEIN yes SCROLL NO  integer
%widget1 SLIDER .runiters 25 step 5 init 15 integer 5 50
%button1 BUTTON KEEP 'APPLY' &sv .test_it = 1; &r iter.aml; &RETURN
%button2 BUTTON KEEP 'EXIT' &RETURN
```

**inivar.aml**

```
/* ************************************************
/* Program: inivar.aml
/* Function: Read in the variable data
/* Called by iter.aml
/* ************************************************

&sv out [close -all]
  &sv .greencap greencap  /* capillary suction head
  &sv .greenk greenk      /* hydraulic conductivity
  &sv .greenpore greenpore    /* effective porosity
  &sv .greensmd greensmd  /* soil moisture deficience

  &if [exists hcur -GRID] &then kill hcur all
  &if [exists hpre -GRID] &then kill hpre all
  &if [exists qx -GRID] &then kill qx all
  &if [exists qy -GRID] &then kill qy all

  &if [exists hydrpara -GRID] &then kill hydrpara all
  &if [exists areap -GRID] &then kill areap all
  &if [exists areac -GRID] &then kill areac all
  &if [exists rivq -GRID] &then kill rivq all
  &if [exists greenaf -GRID] &then kill greenaf all
  &if [exists greenf -GRID] &then kill greenf all


&if ( %.optype% = 3 ) &then
  &do
    &sv initunit [open %.initxt% status -read]
    &sv .channeltype [read %initunit% instatus]
    &sv .rivrough    [read %initunit% instatus]
    &sv .initinlet   [read %initunit% instatus]
    &sv .initq       [read %initunit% instatus]
    &sv .bwidth      [read %initunit% instatus]
    &sv .initarea    [read %initunit% instatus]
    &sv .initdepth   [read %initunit% instatus]
    &if ( %.channeltype% = 1 ) &then
      &do
        &sv .zz    [read %initunit% instatus]
        &sv .z2p1   [SQRT [calc %.zz% * %.zz% + 1] ]
      &end
    &describe %.elev%
    &sv .xmin = %GRD$XMIN%;   &sv .ymin = %GRD$YMIN%
    &sv .xmax = %GRD$XMax%;   &sv .ymax = %GRD$yMax%
```

```
&sv .cellsize  = %GRD$dx%; &sv .diasize = %.cellsize% * 1.414
&sv .sqrsize = %.cellsize% * %.cellsize%

/* Initial Values and Grids and Coverages
&sv .filevar = [open %.varfile% openstatus -write]
&sv out  = [write %.filevar% %.elev%]
&sv out  = [write %.filevar% %.raindat%]
&sv out  = [write %.filevar% %.rainstcov%]
&sv out  = [write %.filevar% %.dirg%]
&sv out  = [write %.filevar% %.sx%]
&sv out  = [write %.filevar% %.sy%]
&sv out  = [write %.filevar% %.roughn%]
&sv out  = [write %.filevar% %.outfile%]
&sv out  = [write %.filevar% %.channeltype%]
&sv out  = [write %.filevar% %.rivrough%]
&sv out  = [write %.filevar% %.initinlet%]
&sv out  = [write %.filevar% %.initq%]
&sv out  = [write %.filevar% %.bwidth%]
&sv out  = [write %.filevar% %.initarea%]
&sv out  = [write %.filevar% %.initdepth%]
&sv out  = [write %.filevar% %.initsm%]
&if ( %.channeltype% = 1 ) &then
  &do
     &sv out  = [write %.filevar% %.zz%]
  &end
&sv out  = [write %.filevar% %.bnks%]

/* ------------- Initial Grids -----------------*/
&if [exists tempdif -GRID] &then kill tempdif all
&if [exists elevdif -GRID] &then kill elevdif all
&if [exists zero -GRID] &then kill zero all

hpre = 0 * %.elev%
qx = 0 * %.elev%
qy = 0 * %.elev%
zero = 0 * %.elev%
greenaf = con(%.elev%, 0.001)

/* assign 0.2 to initial soil moisture
&if [exist %.greensmd% -GRID] &then  kill %.greensmd% all
%.greensmd% = %.greenpore% - %.initsm% /* initSoilMoisture

areap  = %.initarea%
rivq = initq

/* initial  elevdif for river and flow rate for the first use.
DOCELL
  tempdif = abs( con( ~
   %.dirg% == 1, ( %.elev%(1,0) - %.elev%)  / %.cellsize%  , ~
   %.dirg% == 2, ( %.elev%(1,1) - %.elev%)  / %.diasize%   , ~
   %.dirg% == 3, ( %.elev%(0,1) - %.elev%)  / %.cellsize%  , ~
   %.dirg% == 4, ( %.elev%(-1,1) - %.elev%) / %.diasize%   , ~
```

```
    %.dirg% == 5, ( %.elev%(-1,0) - %.elev%)  / %.cellsize%  , ~
    %.dirg% == 6, ( %.elev%(-1,-1) - %.elev%) / %.diasize%   , ~
    %.dirg% == 7, ( %.elev%(0,-1) - %.elev%)  / %.cellsize%  , ~
    %.dirg% == 8, ( %.elev%(1,-1) - %.elev%)  / %.diasize%   ) )
  END
  elevdif = con(tempdif gt 0.05, 0.05, ~
          tempdif le 0.005, 0.005, tempdif)
  kill tempdif all
  /* check the roughness grid exists or not.
  &if [exists %.roughn% -grid ] &then
    &do; kill %.roughn% all; &end

  %.roughn% = con(%.elev%, 0.1)

 &sv .fileunit = [open %.outfile% openstatus -write]
 &sv out [close %.fileunit%]

 &end

&else &if ( %.optype% = 4 ) &then
 &do
 /* Initial Values and Grids and Coverages
 &sv .filevar = [open %.varfile% openstatus -read]
   &sv .elev        [read %.filevar% inst]
   &sv .raindat     [read %.filevar% inst]
   &sv .rainstcov   [read %.filevar% inst]
   &sv .dirg        [read %.filevar% inst]
   &sv .sx          [read %.filevar% inst]
   &sv .sy          [read %.filevar% inst]
   &sv .roughn      [read %.filevar% inst]
   &sv .outfile     [read %.filevar% inst]
   &sv .channeltype [read %.filevar% inst]
   &sv .rivrough    [read %.filevar% inst]
   &sv .initinlet   [read %.filevar% inst]
   &sv .initq       [read %.filevar% inst]
   &sv .bwidth      [read %.filevar% inst]
   &sv .initarea    [read %.filevar% inst]
   &sv .initdepth   [read %.filevar% inst]
   &if ( %.channeltype% = 1 ) &then
     &do
       &sv .zz   [read %.filevar% inst]
       &sv .z2p1  [SQRT [calc %.zz% * %.zz% + 1] ]
     &end
   &sv .bnks        [READ %.filevar% inst]

  copy hpreold     hpre
  copy greenfold   greenf
  copy greenafold  greenaf
  copy qxold       qx
  copy qyold       qy
  copy rivqold     rivq
  copy areapold    areap
```

```
 &describe %.elev%
 &sv .xmin = %GRD$XMIN%;   &sv .ymin = %GRD$YMIN%
 &sv .xmax = %GRD$XMax%;   &sv .ymax = %GRD$yMax%
 &sv .cellsize  = %GRD$dx%; &sv .diasize = %.cellsize% * 1.414
 &sv .sqrsize = %.cellsize% * %.cellsize%
 &sv .fileunit = [open %.outfile% openstatus -APPEND]
 &sv out [close %.fileunit%]

&end

&sv .rainstcov = [entryname %.rainstcov%]
/* this varible here because .optype = 4 should read .rainstcov in
/* before the process.

/* ++++ Open Cursors for data read and write ++++
/* start stcur and assign the .st%i% variables
/* &r raincov.aml

&sv out [close -all]
&sv curcheck = [show cursors]
&if [keyword raincur %curcheck%] > 0 &then CURSOR  raincur REMOVE
&if [keyword stcur %curcheck%] > 0   &then CURSOR  stcur REMOVE
&if [keyword idcur %curcheck%] > 0   &then CURSOR  idcur REMOVE
CURSOR raincur DECLARE %.rainstcov% point  RW
CURSOR raincur OPEN
&sv .rainstno %:raincur.AML$NSEL%
CURSOR stcur DECLARE %.raindat% INFO RO
CURSOR stcur OPEN
&sv .raintime %:stcur.AML$NSEL%
CURSOR idcur DECLARE strnad27.pat INFO RO
CURSOR idcur OPEN
&sv .strno %:idcur.AML$NSEL%


&sv t1 = %:stcur.time% * 60
CURSOR stcur NEXT
&sv t2 = %:stcur.time% * 60
&sv .deltat =  [calc %t2% - %t1%]
CURSOR stcur FIRST

CURSOR raincur FIRST
&sv i = 1
&do &while  %i% <= %.rainstno%
  &sv .st%i% = [value :raincur.%.rainstcov%-ID]
  &sv i = %i% + 1
  CURSOR raincur NEXT
&end
CURSOR raincur REMOVE
```

```
&if [exists fveloc -GRID] &then kill fveloc all
 fveloc = rivq / areap

&describe fveloc
&sv .courant = %.cellsize% / %GRD$ZMAX%
&if %.courant% gt %.deltat% &then &sv .courant = %.deltat%

&if ( %.optype% = 3 ) &then
 &sv .checkt = %.courant%
&else &if ( %.optype% = 4 ) &then
  &do; &sv .checkt = %.courant% + %.stopiter% * %.deltat%; &end

&return
```

**iter.aml**

```
/************************************************************
/* Program: iter.aml
/* Function: 1. Proceed the saint venant equation
/*          2. Fully explicit finite difference with deltat
/*             varied by stream flow velocity.
/*          3. Manning equation for channel flow.
/*          4. Green-Ampt equation for infiltration flow.
/*             (conditionalized)
/*          5. Save information and grid at specific time
/*             period in order for retrieve
/*          6. IDW for rainfall intensity interpolation
/*
/* Called by: wshms.menu (saintnew.menu or saintold.menu)
/*       Chi-Chuan Chen 2nd ed 1996
/*                      April 22 1996
/************************************************************


  mape %.elev%

 /* read in some of the variable names & values */
  &r inivar.aml

 /* Setup the iteration time based on the */

 &if ( %.optype% = 3 ) &then
  &do
    CURSOR stcur FIRST
    &sv iter = 1
    &if ( %.raintime% > %.runiters% ) &then
      &sv .raintime = %.runiters%
  &end

 &if ( %.optype% = 4 ) &then
  &do
    &sv iter = %.stopiter% + 1
    CURSOR stcur %iter%
```

```
  &if ( %.raintime% > ( %.stopiter% + %.runiters% ) ) &then
  &sv .raintime = %.stopiter% + %.runiters%
 &end

/* ++++++ Begin the Simulation Iteration ++++++ */
&DO &while %iter% <= %.raintime%
  &sv .ittime = %iter% * %.deltat%
  &type %iter% iteration to %.ittime% seconds

  /* get the rainfall data from %.raindat% to %.rainstcov%
  /* then create a rain grid using IDW.

    &if ( %:stcur.AML$NEXT% ) &then
     &DO
      CURSOR raincur DECLARE %.rainstcov% point  RW
      CURSOR raincur OPEN
      &sv j = 1
      &do &while %j% <= %.rainstno%
       &sv :raincur.rain  [value :stcur.st[value .st%j%]]
       &sv j = %j% + 1
       CURSOR raincur NEXT
      &end
      CURSOR raincur REMOVE

      &if [exists raing -GRID]  &then kill raing  all
      raing = IDW ( %.rainstcov%, rain, #, 2, SAMPLE, 6, #,~
          %.cellsize%, %.xmin%, %.ymin%, %.xmax%, %.ymax%)~
          / %.deltat%
     &END    /* -- Rainfall & Cursor & IDW -- */


&DO &while %.checkt% <= %.ittime%

 /*   22 ---- Overland Flow Depth ---- 22
 /* For each iteration flow_rate.aml support the lateral flow
 /* for manning.aml to calculate the channel flow rate (riverq)
 /* Calculate infiltration rate at time t + deltat / 2
 /* Calculate infiltration rate at time t + deltat / 2


 &if [exists greenf -GRID] &then  kill  greenf all
 &if [exists hcur -grid ] &then rename hcur hpre

 DOCELL
  tempgf := ~
     (%.greenk% * %.courant% - 2 * greenaf + ~
     sqrt( sqr(%.greenk% * %.courant% - 2 * greenaf) + ~
     8 * %.greenk% * %.courant% * ( greenaf + ~
     %.greencap% * %.greensmd% ) ) ) / 2

     /* this tempgf = greenf * deltat   */
```

```
hh := con( isnull( %.covws%/qx(1,0) ) & isnull( %.covws%/qy(0,1) ), ~
    hpre +  raing * %.courant% + ( qx + qy)~
    * %.courant% / %.cellsize%, ~
    isnull( qx(1,0)), hpre +  raing * %.courant% ~
    + ( qx + qy - qy(0,1) ) * %.courant% ~
    / %.cellsize%, ~
    isnull( qy(0,1) ), hpre + raing * %.courant% ~
    + ( qx + qy - qx(1,0) ) * %.courant% / %.cellsize%, ~
    hpre + raing * %.courant% +  ( qx + qy - qx(1,0) - ~
    qy(0,1) ) * %.courant% / %.cellsize% )

  greenf = con( hh  > tempgf, tempgf, hh)

  /* this .greenf = actural infiltrated amount during delta t */

  hh2 := con( hh  > tempgf, hh - tempgf, zero)
  hcur = con( isnull(%.dirg%), hh2, 0) /* move head away from river cells

END

 &if [exists preaf -GRID] &then kill  preaf all

 preaf = greenaf
 kill greenaf all

 /* Cumulative Infiltration Rate F at time t
greenaf = preaf + greenf
kill hpre all

/*  33 ------ Begin of Friction Slope ------ 33
/* &r friction_slope.aml
&if [exists sfx -grid] &then  kill sfx all
&if [exists sfy -grid] &then  kill sfy all

DOCELL
 sfx1 := con( isnull(%.covws%/hcur(-1,0)), %.sx% - %.covws%/hcur~
      / %.cellsize%,%.sx% - (%.covws%/hcur - %.covws%/hcur(-1,0))~
      / %.cellsize%)

 sfx = con(isnull(%.dirg%) & isnull( %.dirg%(-1,0) ), sfx1,~
         isnull(%.dirg%), - %.bnks%,  %.bnks%)
 sfy1 := con( isnull(hcur(0,-1)), ~
          %.sy% - hcur / %.cellsize%, ~
          %.sy% - (hcur - hcur(0,-1)) / %.cellsize%)
 sfy = con(isnull(%.dirg%) & isnull( %.dirg%(0,-1) ), sfy1,~
         isnull(%.dirg%), - %.bnks%,  %.bnks%)
END

/*  -------- Overland Flow Rate -------- */
/* &r flow_rate.aml
&if [exists qx -grid] &then  kill qx all
&if [exists qy -grid] &then  kill qy all
```

```
/* x-direction (column) sfx > 0 ==> (i,j-1)-->(i,j) */

DOCELL
 qx = con( isnull( %.covws%/hcur(-1,0) ), 0 * %.covws%/hcur,~
    %.covws%/sfx > 0, ~
   pow( %.covws%/hcur(-1,0) , 1.6667 ) * sqrt( %.covws%/sfx ) / %.covws%/%.roughn%(-1,0), ~
   pow( %.covws%/hcur , 1.6667 ) * sqrt( %.covws%/sfx * (-1) ) / %.covws%/%.roughn% * (-1) )

END

/* y-direction (row) sfy > 0 ==> (i-1,j)-->(i,j) */
DOCELL

 IF  (isnull( %.covws%/hcur(0,-1) ) )  %.covws%/qy =  0 * hcur
 ELSE IF (sfy > 0)  %.covws%/qy =  pow( %.covws%/hcur(0,-1), 1.6667)~
       * sqrt(sfy) / %.covws%/%.roughn%(0,-1)
 ELSE    %.covws%/qy =  pow( hcur, 1.6667) * ~
       sqrt(sfy *(-1)) / %.covws%/%.roughn% * (-1)
 ENDIF
END


/* 55 ---------- Manning Channel Routing ---------- 55
/* &r manning.aml
/* Existing temporary GRID Prevention

&if [exists dqdx -GRID] &then  kill dqdx all

DOCELL
 dum1 := con(isnull(%.dirg%(-1,0)) & %.dirg%, 0, ~
   %.dirg%(-1,0) == 1 & %.covws%/rivq(-1,0) , %.covws%/rivq(-1,0), 0)
 dum2 := con(isnull(%.dirg%(-1,-1)) & %.dirg%, 0, ~
   %.dirg%(-1,-1) == 2 & %.covws%/rivq(-1,-1) , %.covws%/rivq(-1,-1), 0)
 dum3 := con(isnull(%.dirg%(0,-1)) & %.dirg%, 0, ~
   %.dirg%(0,-1) == 3 & %.covws%/rivq(0,-1), %.covws%/rivq(0,-1), 0)
 dum4 := con(isnull(%.dirg%(1,-1)) & %.dirg%, 0, ~
   %.dirg%(1,-1) == 4 & %.covws%/rivq(1,-1) , %.covws%/rivq(1,-1), 0)
 dum5 := con(isnull(%.dirg%(1,0)) & %.dirg%, 0, ~
   %.dirg%(1,0) == 5 & %.covws%/rivq(1,0) , %.covws%/rivq(1,0), 0)
 dum6 := con(isnull(%.dirg%(1,1)) & %.dirg%, 0, ~
   %.dirg%(1,1) == 6 & %.covws%/rivq(1,1) , %.covws%/rivq(1,1), 0)
 dum7 := con(isnull(%.dirg%(0,1)) & %.dirg%, 0, ~
   %.dirg%(0,1) == 7 & %.covws%/rivq(0,1) , %.covws%/rivq(0,1), 0)
 dum8 := con(isnull(%.dirg%(-1,1)) & %.dirg%, 0, ~
   %.dirg%(-1,1) == 8 & %.covws%/rivq(-1,1) , %.covws%/rivq(-1,1), 0)

 dum9 := dum1 + dum2 + dum3 + dum4 + dum5 + dum6 + dum7 + dum8

 dqdx = con(dum9 == 0 and (%.covws%/rivq - %.initinlet%) le 0, 0,~
       dum9 == 0, (%.covws%/rivq - %.initinlet%) / %.cellsize%~
```

```
      ,( %.covws%/rivq - dum9 ) / %.cellsize%)

END

  /* lateral flow from overland
  &if [exists %.covws%/lqx  -GRID] &then  kill %.covws%/lqx  all
  DOCELL
   IF ( isnull( %.dirg%(0,1) ) & isnull( %.covws%/qy(0,1)) & %.dirg% )
     dum1 := 0
   ELSE IF ( isnull(%.dirg%(0,1)) & %.covws%/qy(0,1)< 0 )
     dum1 := - %.covws%/qy(0,1)
   ELSE   dum1 := 0

   IF ( isnull( %.dirg%(0,-1) ) & isnull( %.covws%/qy(0,-1)) & %.dirg% )
     dum2 := 0
   ELSE IF ( isnull(%.dirg%(0,-1) ) & %.covws%/qy(0,-1)< 0 )
     dum2 := -  %.covws%/qy(0,-1)
   ELSE   dum2 := 0

   IF ( isnull( %.dirg%(1,0) ) & isnull( %.covws%/qx(1,0)) & %.dirg% )
     dum3 := 0
   ELSE IF ( isnull(%.dirg%(1,0)) & %.covws%/qx(1,0)< 0 )
     dum3 := -  %.covws%/qx(1,0)
   ELSE   dum3 := 0

   IF ( isnull( %.dirg%(-1,0) ) & isnull( %.covws%/qx(-1,0)) & %.dirg% )
     dum4 := 0
   ELSE IF ( isnull(%.dirg%(-1,0) ) & %.covws%/qx(-1,0)< 0 )
     dum4 := -  %.covws%/qx(-1,0)
   ELSE    dum4 := 0

   %.covws%/lqx = dum1 + dum2 + dum3 + dum4
  END

  /* Combine the Components to make the cross area update
  &if [exists %.covws%/areap -GRID] & [exists %.covws%/areac -GRID] &then
     &do; kill %.covws%/areap all;rename areac areap;&end
     /* abs to try cellvalue command

  &if [exists %.covws%/temparea -GRID] &then kill %.covws%/temparea
  %.covws%/temparea = %.covws%/areap  + ( %.covws%/lqx + %.covws%/raing * %.cellsize%~
          - %.covws%/dqdx ) * %.courant%

 &describe %.covws%/temparea
 &type temparea %GRD$ZMAX% %GRD$ZMIN%

  %.covws%/areac = con(%.covws%/temparea ge 0, %.covws%/temparea, %.covws%/temparea < 0, 0 )

  &if [exists %.covws%/depc -GRID] &then  kill %.covws%/depc all
 &if [exists %.covws%/hydrpara -GRID] &then kill %.covws%/hydrpara all

 &if ( %.channeltype% = 1 ) &then
```

```
 &do
   %.covws%/depc = %.covws%/areac / ( %.zz% + %.bwidth% )
   %.covws%/hydrpara = %.covws%/areac / ( %.bwidth% + 2 * %.z2p1% * depc )
 &end
&else &if ( %.channeltype% = 2 ) &then
 &do
   %.covws%/depc = %.covws%/areac / %.bwidth%
   %.covws%/hydrpara = %.covws%/areac / (2 * %.covws%/depc + %.bwidth%)
 &end

&if [exists %.covws%/fveloc -GRID] &then kill %.covws%/fveloc all
&if [exists %.covws%/rivq -GRID] &then kill %.covws%/rivq all

%.covws%/fveloc =  pow(%.covws%/hydrpara, 0.6667) * ~
            pow(%.covws%/elevdif,0.5) / %.rivrough%

%.covws%/rivq = %.covws%/fveloc * %.covws%/areac

&describe %.covws%/fveloc
&sv .courant = %.cellsize% / %GRD$ZMAX%
&type time step %.courant%

/* 66 ------------ Saint Output ------------ 66

CURSOR idcur FIRST
&sv j = 1
&do &while %j% <= %.strno%
  &sv st%j% = [show cellvalue rivq %:idcur.X-COORD%~
          %:idcur.Y-COORD%]
  &sv stid%j% = %:idcur.strnad27-id%
  CURSOR idcur NEXT
  &sv j = %j% + 1
&end

/*  open, write then close the fileunit   ----------
&sv .fileunit = [open %.outfile% openstatus -append]
&sv j = 1
&do &while %j% <= %.strno%
  &sv xx = [quote %iter% %:stcur.time% %.checkt% st[value stid%j%] [value st%j%] ]
  &sv out = [write %.fileunit%  %xx%]
  &type %xx%
  &sv j = %j% + 1
&end

&if ( %.courant% gt %.deltat% ) &then &sv .courant = %.deltat%
&if ( %.checkt% = %.ittime% ) &then &sv .checkt = %.checkt% + %.courant%
&else &if ( %.checkt% + %.courant% > %.ittime% ) &then
    &do
      &sv .courant = %.ittime% - %.checkt%
      &sv .checkt = %.ittime%
    &end
&else &sv .checkt = %.checkt% + %.courant%
```

```
  &type %iter% %xx%

  &sv ttt [close  %.fileunit%] /* close the fileunit

  &END                  /* Loop Ittime -------

  &r plotsaint.aml         /* Plotting -----------

/*  &if ( [MOD %iter% 5 ] = 0 ) &then
   &do

    &if [exists rainold -GRID] &then kill rainold all
    copy  raing rainold
    &if [exists hpreold -GRID] &then kill hpreold all
    copy  hcur hpreold
    &if [exists qxold -GRID] &then kill qxold all
    copy  qx qxold
    &if [exists qyold -GRID] &then kill qyold all
    copy  qy qyold
    &if [exists rivqold -GRID] &then kill rivqold all
    copy  rivq rivqold
    &if [exists greenfold -GRID] &then kill greenfold all; copy  greenf greenfold
    &if [exists greenafold -GRID] &then kill greenafold all; copy  greenaf greenafold
    &if [exists areapold -GRID] &then kill areapold all ; copy  areac areapold
   &end
  CURSOR stcur NEXT
  &sv iter = %iter% + 1
&END          /* Loop iter

  &sv exitstatus = [close %.fileunit%]

&return
```

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